Rural E-mail System for the Sumbandila Satellite

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at the University of Stellenbosch

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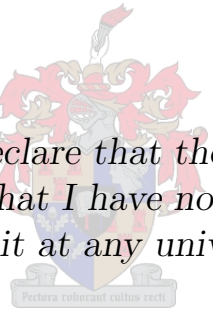
Declaration



I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

SIGNATURE DATE

Abstract

Keywords: digital signal processing, OSI layer, network protocols, embedded systems, satellite technology

This thesis describes the design and implementation of a rural e-mail system for the Sumbandila satellite. The rural e-mail system was developed during a project sponsored by the Department of Communications of the South African government. The complete Open Systems Interconnect (OSI) layer structure of the protocol architecture used on the satellite hardware and software is described. The equivalent implementation of the OSI layer on the ground station hardware is given. This includes the adaptation of the `soundmodem` Open Source Software modem to work for the e-mail system's OSI layer. The design of the Application Layer e-mail system is described and the implementation of this design using the Python, Korn Shell and C programming environments is also given. The procedures used to test the system for reliability and the use of a database to create detailed logs of the e-mail system is shown to have generated a reliable system that is easily maintained. A critical evaluation of the system is provided in the last chapter.

Opsomming

Sleutelwoorde: Syferseinverwerking, OSI-lae, netwerkprotokolle, toegewyde stelsels, satelliettegnologie

Hierdie tesis beskryf die ontwerp en implementering van 'n plattelandse e-posstelsel vir die Sumbandila satelliet. Die plattelandse e-posstelsel is ontwikkel in opdrag van die Departement van Kommunikasie van die Suid-Afrikaanse regering. Die volledige Open Systems Interconnect (OSI) laagstruktuur van die protokol-argitektuur wat in die satelliet se apparatuur en programmatuur gebruik is, word beskryf. Die ekwivalente implementering van die OSI-laag op die grondstasie-apparatuur word gegee, insluitende die aanpassing van `soundmodem`, 'n oopbronkode sagteware-modem. Hierdie sagteware-modem word gebruik in die e-posstelsel se fisiese laag. Die ontwerp van die toepassingslaag van die e-posstelsel word beskryf, asook die implementering van hierdie ontwerp met behulp van Python, die Korn-interpreteerder en C. Die prosedures waarvolgens stelselbetroubaarheid getoets is, en die gebruik van 'n databasis om noukeurige joernale van e-postransaksies te hou, demonstreer dat 'n betroubare, onderhoubare stelsel geïmplementeer is. In die laaste hoofstuk word die stelsel krities geëvalueer.

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Nomenclature

Acronyms

AC	Alternating Current.
AF	Audio Frequency.
ALSA	Advanced Linux Sound Architecture.
AMSAT	The Radio Amateur Satellite Corporation.
API	Application Programming Interface.
APRN	Amateur Packet Radio Network.
ATFTP	Advanced Trivial File Transfer Protocol.
BER	Bit Error Rate.
CAN	Controller Area Network.
CRC	Cyclic Redundancy Check.
DC	Direct Current.
ECC	Error Correction Code.
FM	Frequency Modulation.
FTP	File Transfer Protocol.
GPL	General Public License.
GSE-EI	Ground Support Equipment Ethernet Interface.
HDLC	High-Level Data Link Control.
ICASA	Independent Communications Authority of South Africa.
IF	Intermediate Frequency.
IMAP	Internet Message Access Protocol.
IP	Internet Protocol.
ISO	International Organisation for Standardization.
ITU	International Telecommunications Union.
KISS	Keep It Simple, Stupid.
KSH	Korn Shell.
LSFR	Linear Shift Feedback Register.
NFS	Network File System.
OBC	On-Board Computer.
OSCAR	Orbital Satellite Carrying Amateur Radio.
OSI	Open Systems Interconnection.
POP	Post Office Protocol.

POSIX	Portable Operating System Interface.
RF	Radio Frequency.
RISC	Reduced Instruction Set Computer.
SEU	Single Event Upset.
SHA-1	Secure Hash Algorithm version 1.
SLIP	Serial Line Protocol.
SMTP	Simple Mail Transfer Protocol.
SUNSAT	Stellenbosch University Satellite.
TCP	Transmission Control Protocol.
TFTP	Trivial File Transfer Protocol.
TNC	Terminal Node Controller.
UDP	User Datagram Protocol.
UHF	Ultra-High Frequency.
VCO	Voltage Controlled Oscillator.
VHF	Very-High Frequency.
VUCU	VHF-UHF Communication Unit.

Variables

symbol	**description**
baud	The number of times a signal changes per second.
	Commonly used to describe the number of symbols per second.
Hz	Hertz
P_s	Packet success rate.
P_n	Probability of no errors.

Terms of Reference

The project on which this thesis is based was commissioned by the Department of Communications of South Africa as client, and the University of Stellenbosch as contractors. The client requirement was the development of a low-bandwidth data relay system that could be used as for short message exchange between rural and urban areas.

The specific constraints of the project were the following:

- All satellite hardware was to be supplied by Sun Space and Information Systems. The ordering and manufacture of the hardware was to run in parallel with the project development, and limited hardware would be available initially.
- No custom development or modification of satellite hardware was to be performed.
- A pair of communications frequencies were to be allocated by the Independent Communications Authority of South Africa (ICASA). The allocation process was to run in parallel with the project development, and a specific allocation of frequencies would not be available for the first few months of the project.

Chapter 1

Introduction

1.1 Project Background

This project describes the design and implementation of the rural e-mail system that was commissioned by the Department of Communications of the South African Government to form part of the Sumbandila Satellite. Sumbandila means "lead the way" in the Thsivenda language [7]. The satellite project was commissioned in 2006 to foster technological innovation in South Africa. The design and implementation of the satellite is performed by the University of Stellenbosch and Sun Space and Information Systems (Pty) Ltd (SunSpace). SunSpace is a provider of satellite technology and the related systems to the aerospace industry. The satellite is designed to have a life span of 3 years in orbit [7].

The Sumbandila satellite has several payloads on board. There is an advanced imaging system. The imaging system will be used for the monitoring and management of disasters such as floods, oils spills and fires [11] for example. The imager is going to have a ground resolution of 6.25 m when orbiting at 500 km from the surface of the earth. The imager has a matrix sensor to take low resolution snapshots. The imager will be able to be positioned for earth image acquisition using a real time joystick system controlled by a ground station operator [7].

There is going to be an experimental payload on the satellite. The experimental payload is designed and administered by the University of Stellenbosch. There are several different components of the experimental payload [24]:

- The radio amateur satellite corporation of South Africa (SA-AMSAT) is placing an amateur radio service on the experimental payload. The amateur radio service will be able to operate in digipeater, parrot and voice beacon mode.

- The Nelson Mandela Metropolitan University is placing a string vibration experiment on the experimental payload. The primary goal of the experiment is to determine the non-linear effects of string dynamics in micro-gravity.

- University of KwaZulu-Natal is placing an experiment on the payload to measure the Earth's magnetosphere. The goal of the experiment is to measure atmospheric

phenomena below 30kHz.

- The University of Stellenbosch is placing a software-defined radio experiment and an experiment to measure the effects of radiation on satellite electronics on the experimental payload

The e-mail system is an independent payload on the satellite which is designed and implemented by the University of Stellenbosch using SunSpace hardware.

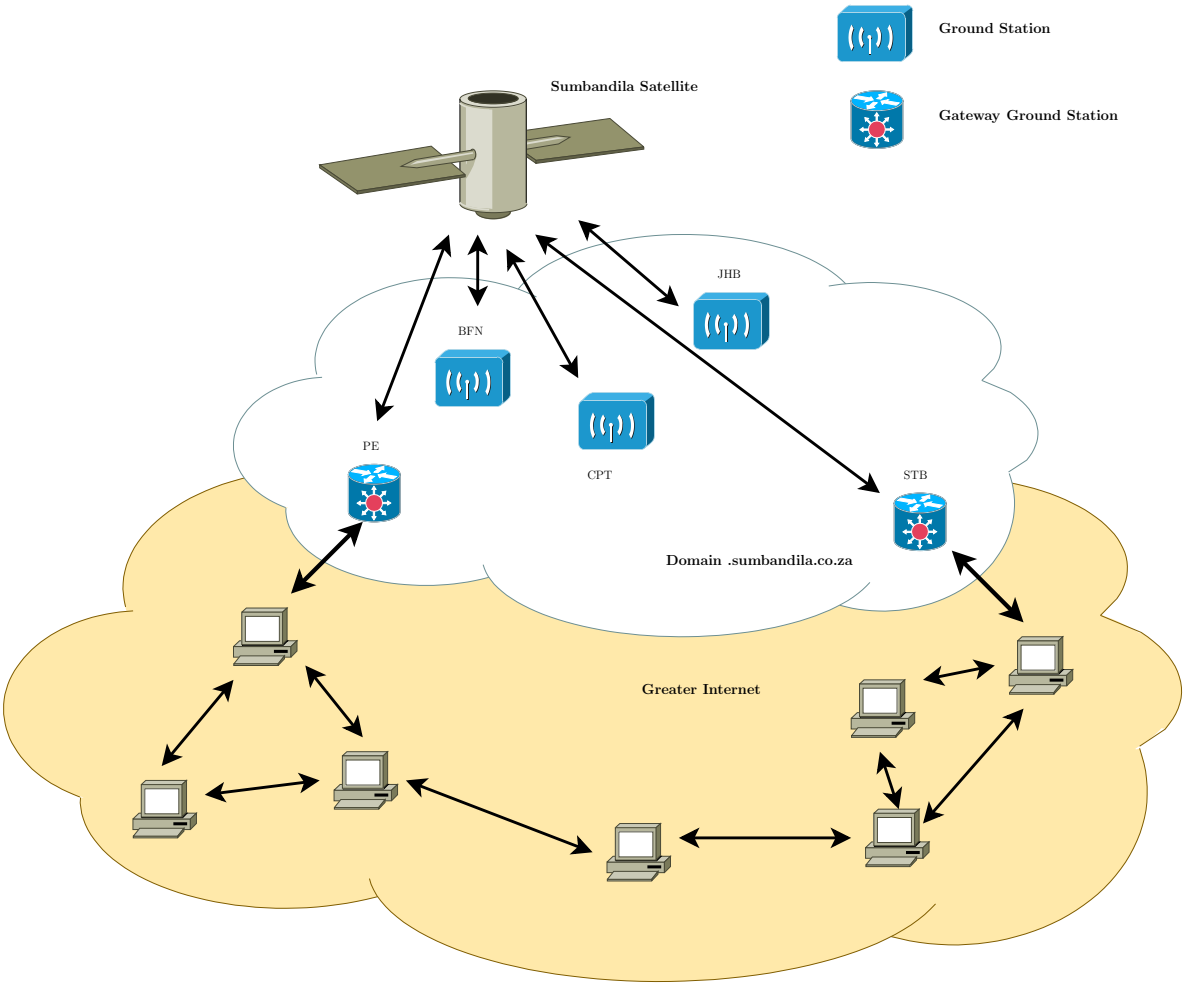

Figure 1.1: *The rural e-mail network layout [25].*

The primary objective of the e-mail system is to provide a global e-mail facility, irrespective of user position, but with the understanding that users will be mobile [27]. Figure 1.1 shows the layout of the rural e-mail network that will be used to achieve this functionality. There are going to be several rural ground stations that do not have access to the Internet. The rural ground stations will be dispersed throughout South Africa. The rural ground stations should be able to communicate with the greater Internet by e-mail.

The ground stations are able to communicate with the Sumbandila satellite. The satellite is to operate as a relay service between the ground stations and the gateway ground stations.

Gateway ground stations have access to the greater Internet and can relay messages from the rural e-mail network to the greater Internet.

The Sumbandila satellite is designed to have a polar orbit. The satellite is to pass over South Africa four times a day and this is the only period when the ground stations will be able to communicate with the satellite. The other payloads on the satellite will also have to communicate with the central control ground station when the satellite passes over South Africa. The passes over South Africa will have to be shared between the different payloads on the satellite because the different payloads are unable to communicate to the ground at the same time.

1.2 Purpose of the Project

The purpose of this project is to implement all the software that must run on the satellite hardware to enable the satellite to act as a relay service between the rural ground stations and the gateway ground stations. The ground station hardware and software must also be designed to complete the e-mail system. An Application Programming Interface (API) must be developed so that ground station users and programs can interact with the e-mail system in a simple and transparent manner.

The project is a commercial project so all steps must be taken to ensure that the system works as a reliable service. The project must be thoroughly tested and must work under all circumstances. The system must be designed to be easy to maintain for the life time of the satellite.

1.3 Structure of the Thesis

This thesis has three main components. The first component describes the characteristics of the system on which the project had to be developed and the problems that had to be solved before the e-mail system could be developed. A description of the satellite hardware and OSI model implementation is given in chapter 2. A description of the implementation of an equivalent protocol layer on the ground station is given in chapter 3.

The second component of the project describes the development and implementation of the e-mail system. Chapter 4 explains how the e-mail system was designed by using diagrams and an example of the upload and download of an e-mail. Chapter 5 describes how the design given in chapter 4 was implemented on the satellite and on the ground station.

The last component of this thesis describes how the system was validated to be reliable and how the system was designed to be easily maintainable. Chapter 6 describes the test environment and the tests that where performed on the system. Chapter 7 shows that the system was designed to be easily maintained. Chapter 8 provides the test results obtained from the tests in chapter 6.

The conclusion gives a critical analysis of the project's final implementation and suggests steps that can be taken to improve the system.

Chapter 2

OSI Layer Constraints

A description of the open systems interconnect (OSI) layer model will be given in this chapter. The structure of the OSI layer that the e-mail system was designed on was largely determined by the hardware and software that SunSpace supplied for the project. This chapter will describe the structure of the OSI layer so that the decisions made in the next chapters can be better understood.

2.1 OSI Model

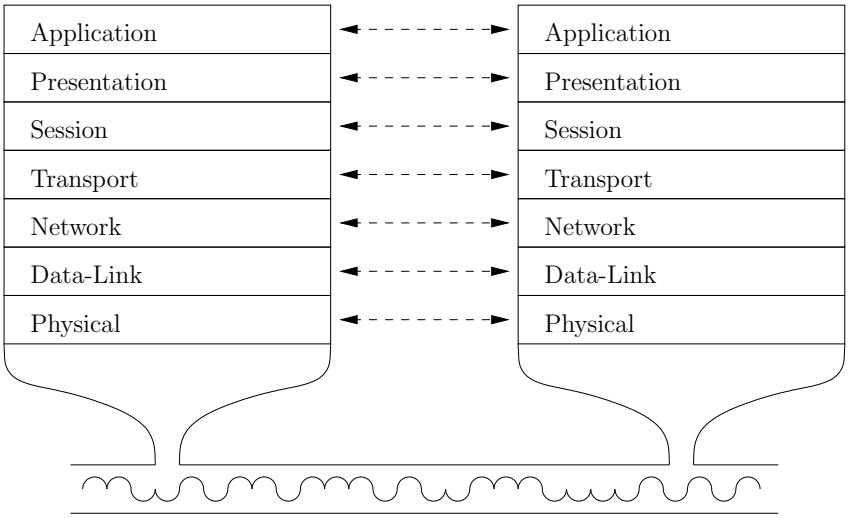

Figure 2.1: *OSI model of the network architecture.*

The International Organisation for Standardization (ISO) developed the 7 layer Open Systems Interconnect (OSI) model to provide a standard way to partition the network functionality of a communications system [18]. Figure 2.1 shows a graphical representation of the OSI model.

A description of the different layers will now be given:

- **Physical Layer**
  The transmission of raw bits are described in this layer. The modulation scheme used to transmit the data over a channel falls within this layer.

- **Data-Link Layer**
  The raw bits transmitted in the physical layer must be understood by higher layers in the model. The data-link layer provides a method to transfer frames of data over the physical layer by providing error-detection, correction and framing of data packets.

- **Network Layer**
  The network layer provides routing between nodes in a packet switched network [18]. A network layer data unit is called a packet while a data-link layer data unit is called a frame.

- **Transport Layer**
  The transport layer provides a transparent transfer of data between end-users on the end hosts. The transport layer data unit is typically called a message. The transport layer typically does not run on intermediate switches and routers.

- **Application Layer**
  The rest of the three layers are all going to be viewed as the Application layer for the purpose of this discussion. Protocols that are used to send files between users on end-hosts run on this layer for example.

2.2 Physical Layer

The VHF UHF Communication Unit (VUCU) that SunSpace manufactures was used as the radio on the satellite for the Communications payload. The VUCU design was influenced by the radio system used in the original Stellenbosch University Satellite (SUNSAT) that the University of Stellenbosch launched on the 23 February 1999.

SUNSAT was an Orbital Satellite Carrying Amateur Radio (OSCAR) [12], which is a satellite that uses amateur radio frequencies to communicate with the earth. The amateur frequencies that were used on SUNSAT were in the UHF and VHF bands. The VUCU was also developed to work in these bands.

As the e-mail system is a commercial project, the standard amateur radio frequencies could not be used for this project. The Independent Communications Authority of South Africa (ICASA) is responsible for managing the assignment of frequencies to bandwidth users in South Africa. The communications payload had to apply to this authority for the up-link frequencies. The International Telecommunications Union (ITU) is responsible for the assignment of frequencies internationally and the frequency for the down-link had to be applied for through this authority.

ICASA and the ITU assigned a separate frequency in the UHF band for the up-link and the down-link. The frequencies that have been assigned are found approximately 0.2 MHz apart. The VUCU does not have adequate hardware capabilities to demodulate the received signal when the VUCU is transmitting because the transmitted signal power is significantly higher than the received signal. Thus the VUCU cannot use full-duplex communication on the channel causing the channel to be used in half-duplex mode.

A further restriction caused by the VUCU is that it was designed to implement full-duplex communication. It is not able to do carrier sensing on the channel and the physical layer protocol used in the VUCU modem does not use collision avoidance.

This has severe restrictions for our application because it means that the VUCU is not able to implement half-duplex communication with any arbitrary higher level protocol. The half-duplex communication must be controlled by the higher level protocol. This problem will be explained in more detail in section 2.4 and the solutions to this problem used in the e-mail system will be discussed in section 3.2 and 3.3.

2.2.1 The VUCU Modem

The VUCU has several different modems implemented on it and the one that is used for the e-mail system is a 9600 baud G3RUH modem. The G3RUH modem is a popular amateur radio modem first described by James Miller [16]. The G3RUH modem is used for the e-mail system because this is the modem that SunSpace runs its higher level protocols over.

The G3RUH Modem uses the High-Level Data Link Control (HDLC) protocol as the data-link layer protocol which will be described in section 2.3.

The implementation of the modem on the satellite and the ground station did not form part of the development of the e-mail system. A brief description of the G3RUH modem is given here to allow the user to have a better understanding of the complete system and a detailed description of the modem can be found in [16].

Transmit:

1. Bits from the data-link layer are sent serially to the modem.

2. Data is then sent through a scrambler (or randomizer) to remove any DC offset. A DC offset can be caused by a long sequence of equal binary data bits being sent to the modem. The scrambler also flattens the spectrum of the modulated signal which helps keep the modulated signal within the specified bandwidth.

3. The scrambler uses a linear feedback shift register (LFSR) to scramble the data.

4. For each bit in the scrambled data a Nyquist pulse [16] is generated. This is achieved by filtering the scrambled data with a finite impulse response (FIR) filter to produce the Nyquist pulse for each bit.

5. The goal of the filter is to decrease the bandwidth used by the signal and the inter-symbol interference between the modulated symbols.

6. The signal generated from the filter is then applied to a voltage control oscillator (VCO) to produce a ±3 kHz deviation Frequency Modulated(FM) signal at an intermediate frequency (IF).

7. The IF signal is then mixed up to the correct radio frequency(RF) and transmitted over the channel.

Receive:

1. The received RF signal is mixed down to the AF signal.

2. The AF signal is then sampled at the correct time to obtain the data bits.

3. This can be achieved by correlating the signal with the matched(time reversed) FIR filter used in the transmit procedure and sampling at the peaks that are obtained from this process [19].

4. The bits are then unscrambled using the same LFSR as in the transmit procedure.

5. The unscrambled bits are then sent up to the data-link layer.

The basic operation of the G3RUH filter has been outlined; the HDLC protocol and Data-Link protocol used by SunSpace will now be described.

2.3 Data-Link Layer

The VUCU uses a subset of the Higher-Level Data Link Control protocol to transmit bits over the link. HDLC is a bit orientated protocol that can work over synchronous and asynchronous links [23]. The structure of a HDLC frame is shown in figure 2.2.

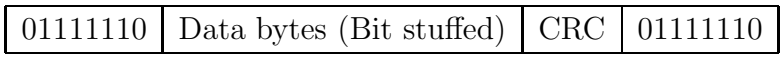

Figure 2.2: *Structure of a Higher-Level Data Link Control (HDLC) frame.*

The protocol uses the unique sequence '01111110' (7E in hexadecimal notation) to frame a packet. Bit stuffing is applied to the data within the packet. Bit stuffing adds a '0' to a sequence of six ones before the sixth one to ensure that the start/stop HDLC sequence does not occur within a data frame. This ensures that a sequence of five ones is followed by a

zero. This makes it impossible for a start or stop sequence to be found in the packet unless a bit error is introduced into the packet.

The sequence at the beginning of the frame is also necessary for the receiving modem to synchronise its clock with the transmitter by using a digital phase lock loop.

A Cyclic Redundancy Code (CRC) is used to distinguish a valid packet from packets where bit errors have been introduced. A CRC adds redundant information to a packet to enable the detection of errors in the packet if they occur. A full description of the functioning of a CRC can be found in [18].

The CRC used in the standard HDLC is described by the CRC-16 polynomial $x^{16} + x^{15} + x^2 + 1$. The reciprocal polynomial of the CRC-16 polynomial is used to generate the CRC used in the SunSpace implementation of HDLC. The reciprocal polynomial is calculated by replacing the x^{16} though x^0 coefficients in the original polynomial with the x^0 through x^{16} coefficients. The only difference that this causes is that the reciprocal polynomial generated CRC is in bit-reversed order to the original CRC. The CRC calculation used in the SunSpace implementation of HDLC starts with an initial value of the CRC set to FFFF in hexadecimal notation.

SunSpace only uses the framing technique of HDLC and uses a custom protocol to describe the contents of the frames. The layout of the frame is shown in figure 2.3.

Figure 2.3: *Structure of the SunSpace custom protocol frame in a HDLC frame.*

The frame structure that SunSpace uses within the HDLC frame is very simple. There are two types of frames: tunneled network traffic and tunneled Controller Area Network (CAN) bus traffic. The transfer of bytes from one VUCU to another VUCU is now known and the protocol that runs on top of the data-link layer is discussed in the next section.

2.4 Transport and Network Layer

The block diagram of the layout of the satellite architecture is shown in figure 2.4. The on-board computer (OBC) that the e-mail system uses on the satellite is also supplied by SunSpace. The OBC has the following components:

- An SH4 processor as its main microprocessor. The SH4 is a 32-bit reduced instruction set computer (RISC) microprocessor produced by the chip manufacturer Renasis.
- 8 Mb of error correction code (ECC) protected synchronous dynamic random access memory (SRAM). The SRAM provides some protection from radiation-induced upsets in the space environment.

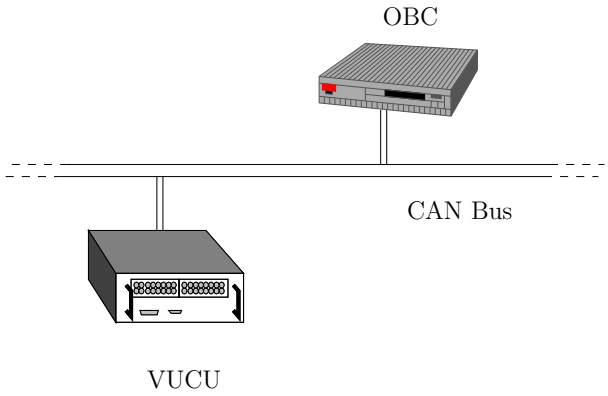

Figure 2.4: *Satellite block diagram of the system layout.*

- Two Cygnal 8051 processors with integrated controller area network (CAN) controllers to connect to the CAN bus.
- Two 8 Mb banks of NOR flash memory where the operating system images and backup file system images are stored.
- Two 256 MB banks of NAND Flash memory where the normal file system is stored.

SunSpace uses the real-time operating system QNX for the OBC, which is able to run on the SH4 processor. QNX is a fully Portable Operating System Interface(POSIX) compliant operating system. POSIX is a standard that is based on the UNIX operating system that was created to enable a standard way for software to interface with the operating system. POSIX was designed to make it possible to write software that can run on different types of operating systems without having to change the original software.

It was decided to use QNX as the operating system for the e-mail system because the project then has access to the same software environment that SunSpace uses. A few reasons for this decision is now discussed. By using QNX, the e-mail system is able to access many of SunSpace's systems. For example it will be possible to update software on the satellite by using the main Telemetry, Tracking and Control communication path if for some reason the e-mail system's communication path fails. This can be done using existing software that SunSpace has written without having to create any new custom software. SunSpace implemented a protocol that runs on the CAN bus. It enables the transmission of telemetry commands and tunneling of network data on the CAN bus.

Access to the CAN Bus is transparent to software running on the QNX operating system because SunSpace has implemented a network driver for QNX. The network driver makes the CAN bus appear as a normal Ethernet hardware device to the QNX network stack. Software running on the SH4 processor is thus able to run a standard network stack. This makes it possible to use the User Datagram Protocol (UDP) or the Transmission Control Protocol

(TCP) as the transport layer protocol and the Internet Protocol (IP) as the network layer protocol.

This creates a transparent transport layer between the OBC and a ground station as long as the ground station also implements the complete network stack as outlined in this chapter. Normal IP traffic is thus able to run over the channel. The e-mail system can then be completely implemented in the application layer.

2.5 Application Layer

The use of the QNX environment also has some added benefits in the application layer. SunSpace created a process monitor program that runs on QNX on the SH4. The process monitor is a program designed to manage user defined programs. The process monitor makes it possible to start and stop a managed program on the OBC using telecommands and also ensures that when a program is started it executes continuously. The program that is developed to implement the e-mail system can be added to the managed programs. The interface to the e-mail system will then be similar to any other payload found on the rest of the satellite.

The e-mail system program runs on a fully functional operating system with a complete network stack. The software can thus be designed as you would design any other software that runs on Linux. The design must only take the following considerations into account:

- The OBC is an embedded environment so there are restrictions on the processing power of the SH4 and the amount of memory available to the application.
- The link is half-duplex and the VUCU is unable to enforce half-duplex operations at the physical layer.

The implication of the second point is that it is impossible to run TCP over the communications channel, which restricts the use of standard higher level protocols such as the File Transfer Protocol (FTP). TCP requires a full-duplex link or a half-duplex link that has hardware that has collision avoidance capabilities to ensure that the link is accessed in a half-duplex manner. The VUCU is not able to do this so UDP must be used as the Transport Layer protocol. The application that uses UDP must then ensure that the channel is accessed in a half-duplex manner.

The OSI layer upon which the e-mail system must be developed on the satellite has now been described. The next chapter will show how an equivalent OSI layer structure was implemented on the ground station hardware. The choice of application layer protocols for the transferring of e-mails will also be described in the next chapter.

Chapter 3

OSI Layer System Design

The e-mail system forms part of the application layer. The design of the e-mail system can be described only after the solutions to the various problems found in the lower layers of the OSI model are given.

The ground stations must be designed to be cost effective because more than one of them are going to be manufactured and distributed across South Africa. Desktop computer hardware is relatively inexpensive and have more than enough resources available for the project to function correctly.

The Linux operating system is copyrighted using the general public license (GPL). This makes it possible to use the operating system freely and gain access to the source code of the operating system because of the way the GPL license is designed [4]. Thus by using the Linux operating system the costs of the ground station as a whole can be reduced because no operating system licenses have to be purchased. Being able to access the source code of the Linux operating system also enables the developer to tailor the operating system to the e-mail system's needs.

To design the e-mail system, a functional ground station had to be developed. It was decided to use a conventional desktop computer and the Linux operating system to develop the ground stations for the reasons described above. Specifically the Ubuntu Linux distribution was used as the operating system on which to develop the software. Ubuntu is similar to Debian and uses the same program packaging techniques as Debian. Debian runs on many different hardware architectures by default [3]. Thus changing the distribution from Ubuntu to Debian should be possible if different hardware to the desktop computer is chosen for the final ground station hardware.

The design of the OSI layer used on the ground station hardware is described in this chapter.

3.1 Physical and Data-Link Layer

If more of the OSI layers are implemented in software on the ground station desktop computer the less the final ground station hardware will cost. The reason for this is that less specialised

hardware will have to be designed or purchased to implement the OSI layer components. Thus it was decided to try implement as much as possible of the OSI layers in software or by using standard desktop hardware components.

Specialised hardware must be used to convert the RF signal down to an AF signal. The conversion is performed by a transmitter or a receiver. The AF signal must be interpreted in the physical layer and a modem performs this function. It is not possible to implement the conversion from RF signal to AF signal without using some kind of specialised hardware. Thus the conversion from RF signal to AF signal could not be implemented in software on the desktop computer. More details on the hardware setup is given in chapter 6.

Once the AF signal is obtained from the RF signal using the specialised hardware, a G3RUH modem must demodulate the signal to generate packets to be passed up to the ground station's transport and network layer. A G3RUH modem must also be used to generate the outgoing AF signal from packets received from the ground stations transport and network layer.

The open source software modem called `soundmodem` written by Thomas Sailor was used to implement the modem used on the ground stations [20]. `soundmodem` uses a standard desktop computer's sound card to capture and generate the AF signal. The software performs all the functionality of a G3RUH modem in software.

`soundmodem` is written to work as a Terminal Node Controller (TNC) on an AX.25 network. AX.25 is a physical and data-link layer protocol that is used on Amateur Packet Radio Networks (APRN) [8, 1].

The AX.25 standard uses HDLC to frame the AX.25 packets. This is useful because the VUCU also uses HDLC to frame the SunSpace data-link layer protocol (see section 2.3). AX.25 uses a different CRC polynomial to generate the checksum that is added to the HDLC frame, as seen in figure 2.2. Thus `soundmodem` had to be modified to use the correct checksum that SunSpace uses for its own HDLC implementation.

Because the AX.25 standard is a data-link layer standard, there are many features that are not suitable for this project. Thus the `soundmodem` software had to be modified to remove the AX.25 data-link layer parsing of the packets within an HDLC frame. The SunSpace data-link layer packet parsing was then added to `soundmodem` so that it could communicate properly with the VUCU.

`soundmodem` also used a sampling frequency of 14400 Hz to sample the received audio at the sound card and to generate the audio for transmission. At this sampling frequency bit errors occurred during transmission and packets where dropped.

Figure 3.1 and figure 3.2 shows the Fast Fourier Transform of the `soundmodem` generated AF signal recorded by a desktop computer using its sound card. `soundmodem` generates the audio signal at 14400 Hz and 44100 Hz respectively. The `soundmodem` generated AF signal is sampled at different frequencies in the sub-plots of the figures to observe the affect that the sampling frequency has on the received audio signal.

Looking at the figures 3.1 and 3.2, it can be deduced that the bandwidth of the signal is

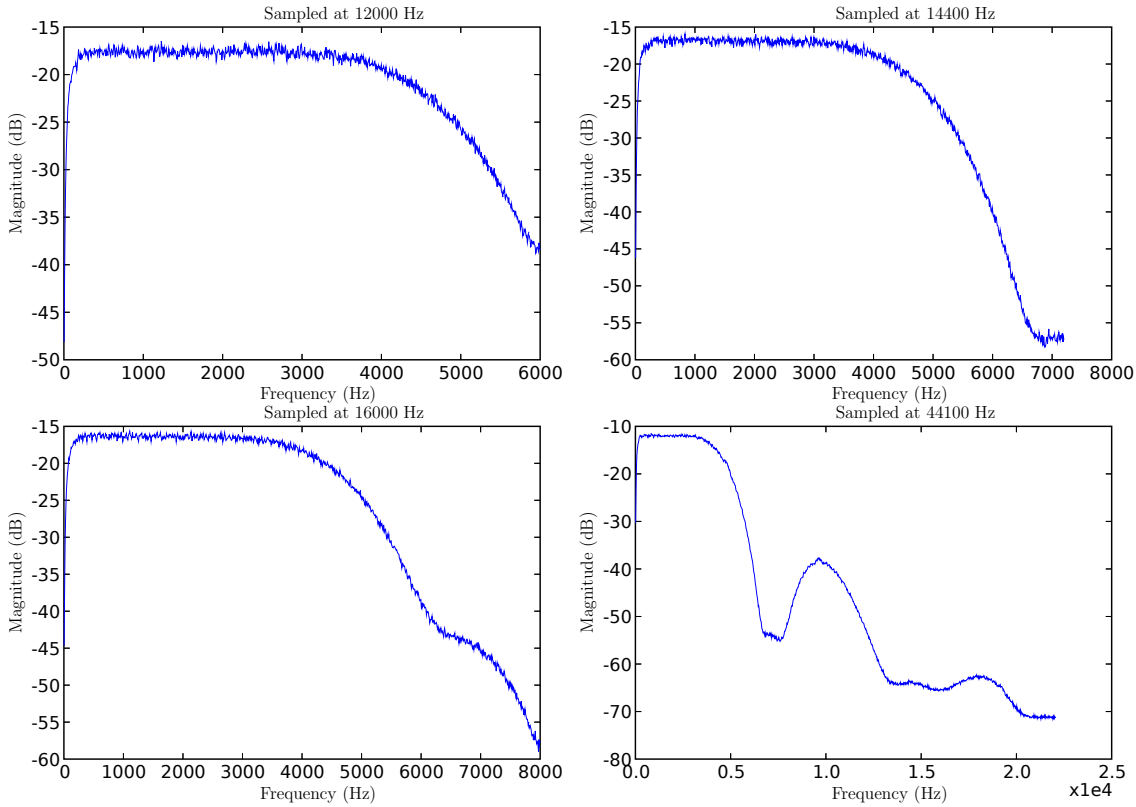

Figure 3.1: *Fast Fourier Transform of the* `soundmodem` *audio signal generated with a sampling frequency of 14400 Hz. In each of the sub-plots, the generated audio signal is sampled at a different frequency using a desktop computers sound card.*

approximately 4200 Hz because the signal drops by about 3 dB at this frequency compared to the signal strength at the lower frequencies. According to Nyquists theorem [28], an exact replication of the audio signal can be reconstructed if the audio signal is band-limited and sampled at more than twice the bandwidth of the audio signal. Thus the signal should be sampled at a minimum of approximately 8400 Hz. The signal should be sampled at a higher frequency than this to compensate for the roll-off of the filter used to band-limit the signal. Thus by adding a 50% margin of error the signal should be sampled at approximately 12600 Hz.

In theory the sampling frequency of 14400 Hz used by `soundmodem` should work. In practice the sampling frequency did not work and there are several reasons for this:

- Most sound cards have a finite set of sampling frequencies at which they are able to sample. The utility `pa_devs` provided by the advanced linux sound architecture (ALSA) can be used to determine the set of sampling frequencies. For most sound cards 14400 Hz is not one of these frequencies. The closest frequencies found on most

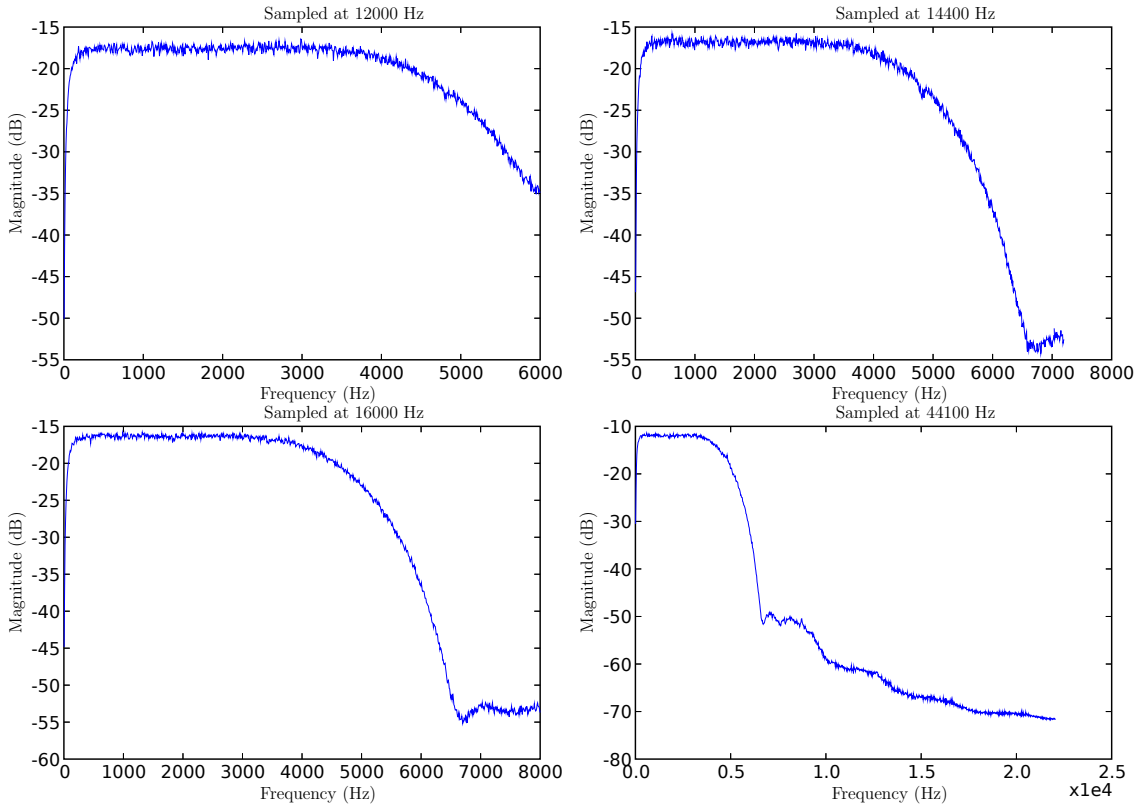

Figure 3.2: *Fast Fourier Transform of the* `soundmodem` *audio signal generated with a sampling frequency of 44100 Hz. In each of the sub-plots, the generated audio signal is sampled at a different frequency using a desktop computers sound card.*

sound cards to 14400 Hz is 12000 Hz on the lower end and 16000 Hz on the higher end. Thus the sound card driver must perform a sample rate conversion from 14400 Hz to 16000 Hz which can cause some errors to be introduced into the signal if the driver is not designed properly. It also adds additional processor overhead.

- The ground stations should try to minimise the costs of the hardware as much as possible. To achieve this the on-board sound card of the motherboard of the desktop computer is used for the sound card. The on-board sound card of a motherboard for a desktop computer is often a very cheaply designed piece of hardware. The filters used to band-limit the audio signal can often not be of a very high quality. This can cause aliasing to be introduced into the sampled signal if it is not sampled with a high enough frequency to compensate for the slow roll-off of the sound card filters.

In figure 3.1 the bottom right plot shows the Fourier Transform of the audio signal when the signal is generated at 14400 Hz and sampled at 44100 Hz. Alias components are

introduced into the signal at 9600 Hz and 19200 Hz which should have been filtered out of the signal by the sound card filter. When the sampling rate for reception is also at 14400 Hz these aliased components are introduced into the desired signal causing bit errors. The aliasing is not noticed in the top right plot in figure 3.1 because the aliasing is of a lower magnitude than the desired signal. This might be good enough for analogue audio but is not good enough for data communication. These harmonics are not nearly as prominent when the signal is generated with a 44100 Hz sampling rate as seen in figure 3.2.

Table 3.1: *Bit error rate when different sampling frequencies are used in* `soundmodem`*. The BER is determined when* 1×10^6 *bits were transmitted.*

Sampling Rate (Hz)	Bit Error Rate ($\times 10^{-6}$)
12000	7102
14400	352
16000	112
22050	0
44100	0

Sound cards can vary dramatically in quality and when choosing a sound card for the ground station a method must be used to determine the bit errors that occur at different sampling frequencies to enable the choice of the optimum frequency to sample at. Table 3.1 shows the bit error rates that are observed when two desktop computers are connected to each other using `soundmodem`. A few of the default sampling rates at which sound cards are able to sample are used for the table. The application `soundmodemconfig` provided by the `soundmodem` software package can be used to predict the bit error rate. The table shows that at 14400 Hz the bit error rate is 352×10^{-6} between the computers over a good audio link. This is unacceptable because virtually no errors should occur over this link.

At 22050 Hz perfect communication is observed. So for the specific setup used for the e-mail system's purposes, 22050 Hz should be an adequate sampling rate used in `soundmodem`. This does not take into account the differences that could be observed between a VUCU generated audio signal and a `soundmodem` generated signal, which could cause the bit error rate to be higher.

Figure 3.3 shows the Fast Fourier Transform of the VUCU audio signal. The signal appears to have approximately the same bandwidth as the `soundmodem` generated signal but has an extra DC component that is a known characteristic found on the VUCU hardware. This DC component is filtered out by the `soundmodem` software.

`soundmodem` was initially not able to communicate with the VUCU but through the changes outlined in this section it was developed into a viable modem to be used on the ground station hardware.

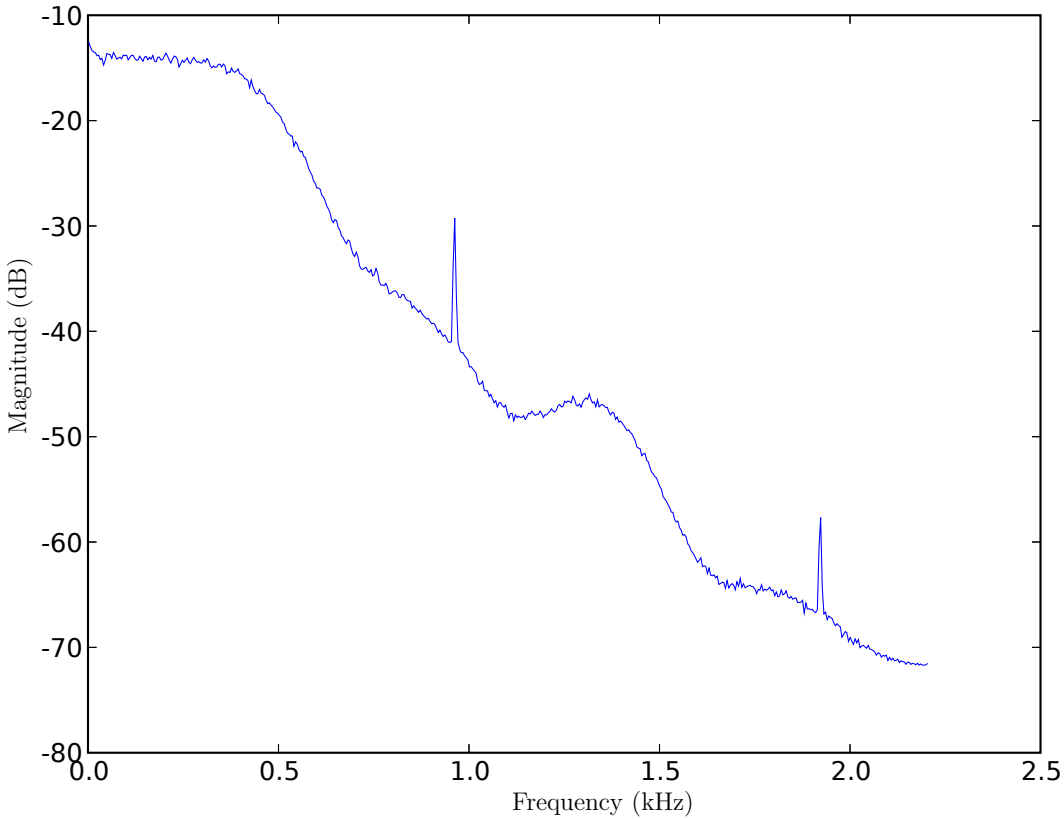

Figure 3.3: *Fast Fourier Transform of the VUCU audio signal sampled at 44100 Hz.*

3.2 Transport and Network Layer

Now that the physical and data-link layer problems have been solved by using `soundmodem`, the packets generated by `soundmodem` must be passed to the Linux network stack and the packets generated by the Linux network stack must be passed to `soundmodem`.

As described earlier, `soundmodem` was developed to be used as part of the AX.25 protocol. The Keep It Simple, Stupid (KISS) protocol that AX.25 uses to connect an AX.25 TNC to a computers network stack is almost the same as the Serial Line Internet Protocol (SLIP) used to connect any arbitrary serial network device to a computers network stack. The only difference is that KISS has TNC control and other functions built into the protocol. These are not necessary for the SunSpace data-link layer protocol.

`soundmodem` uses a pseudo terminal, which is an emulated terminal in Linux, to make the modem appear as a normal serial AX.25 TNC to the Linux network stack.

SLIP is normally used to connect to a serial port modem and works over a point-to-point link. SLIP and KISS simply frame the packets that are placed into the pseudo terminal with a unique character at the beginning and end of the packet and then escapes any of

these characters that are found within the packet. This is a similar process that the HDLC protocol uses in section 2.3. The Linux network stack can then use the framing protocol used by SLIP and KISS to retrieve the packets from the pseudo terminal. Thus by removing all the TNC control from `soundmodem`, `soundmodem` can be made to look like a normal SLIP modem because SLIP uses the same framing protocol as KISS.

The Linux utility slipattach is used to connect the pseudo terminal to the Linux network stack. `soundmodem` is then viewed as a normal network device and all of the Linux network utilities are available to this device.

Thus the transport layer, namely UDP, is functional on the ground station.

3.3 Application Layer

In section 2.5 it was shown that the application layer protocol should use UDP to communicate and should not have unnecessary overhead to reduce the load on the OBC. The protocols should also access the link in a half duplex manner. Two protocols, namely the Network File System (NFS) and Trivial File Transfer Protocol (TFTP) were isolated as potential candidates for these protocols.

3.3.1 NFS

NFS is a widely used distributed file system that was originally developed by Sun Microsystems, Inc. QNX has a NFS client and server available for use on the system. The NFS client can only use NFS protocols 2 and 3. Several properties of the NFS protocol version 3 is now discussed:

- NFS has two components, namely a client and a server.
- NFS is able to run over UDP and works in a lock-step protocol. Because the system uses a lock-step protocol, only one packet is transmitted over the link at one time. This is perfect for the half-duplex link used for this project.
- NFS uses Sun's remote procedure call library to implement the protocol.
- NFS allows the distributed file system to be viewed like a normal part of the file system to the client machine. Thus files can be copied, moved, renamed and listed like any other file in the file system. This makes it trivial to implement the e-mail system because files can be simply moved from remote directories to local directories or vice versa.
- NFS requires the distributed file system to be mounted and unmounted.
- There is authentication when a client mounts the NFS file system and during all transfers of files using a variety of different authentication techniques [9].

Testing the NFS protocol over the audio link using the QNX NFS client showed that it worked successfully. The overhead involved using NFS is quite severe when compared to TFTP and these results will be shown in section 8.2.

3.3.2 TFTP

TFTP is a very simple file transfer protocol that is often used for devices like routers to boot off the network. A few properties of the protocol is now described:

- It uses a lock-step protocol to transfer files from a client to a server or vice versa.
- There is no connection setup or termination. The client simply requests to read a file or write to a file and the transfer begins immediately. Thus there is virtually no overhead involved before transferring a file.
- There is no host authentication or security used to protect the system from malicious users. Thus this authentication must be implemented by the e-mail system.
- TFTP is unable to list the contents of a directory. This means that lists of files to upload and download need to be created so that the e-mail system knows which files to transmit.
- The file is broken up into 512 byte blocks and transferred in a lock-step protocol. This creates a problem because the utilization of the satellite link cannot be optimised if the packet size cannot be changed.

Request For Comments (RFC) 1350 [21] provided by the Internet Engineering Task Force (IETF) provides a detailed specification of the protocol.

QNX has a TFTP client and server as a default part of the system. This implements the basic RFC 1350. The QNX TFTP client is closed source but it seems to use a blocking socket call when trying to read or write to a UDP socket. A socket is a method to access the network stack described in the socket application program interface (API) which is described in [18, 22]. Thus the client can block on a socket call when waiting for data to be read from the socket for example. This causes the link to be used inefficiently if the bit error rate is bad because data might not arrive at the socket to be read by the client. The client will then never be able to carry on with any other processing. An alternative client was required to fix this problem.

RFC 2347 [14], 2348 [13] and 2349 [15] propose the following modifications to the protocol that are very useful for the e-mail system:

- RFC 2347 defines a method whereby protocol parameters can be passed between a server and clients in a backwards compatible manner.

- RFC 2348 defines an option whereby the blocksize used in the lock-step protocol can be negotiated between the client and the server. This is very useful for our application because the utilization of the satellite link can be optimised by selecting a packet size that achieves the largest packet throughput for the link by adjusting the size of the packet for the bit error rate that is observed on the channel.

- RFC 2349 defines options whereby the timeouts used on the client and server during file transfer can be set. This is essential to optimise the usage of the satellite link because it provides a deterministic method of controlling how long a ground station will try to use the link (when the link fails) before the client keeps quiet.

The Linux ATFTP package contains a client and server which implement the extensions just described. ATFTP also uses blocking socket calls to access the network stack, but it uses a method whereby the socket is only read from if something has arrived from the network stack. It uses the "select" POSIX system call to achieve this. Thus the system does not block and the timeouts that it uses are much more reliable than the default TFTP client used on QNX.

The ATFTP package had to be ported to the QNX operating system. The ATFTP package seems to be well designed and cross-compiling the package was straightforward. The following problems where fixed to make ATFTP work properly on QNX and are common problems found when cross-compiling to QNX:

- In Linux the threading library `libpthread` is not part of the standard C library while in QNX it is part of the standard library. Thus the libraries specified to the compiler had to be changed to make the package link successfully.

- The QNX operating system does not have the `sys\types.h` C header file. So an equivalent header file for QNX was created.

- The OBC uses a reduced functionality TCP/IP stack on QNX. Some of the socket API functions are not implemented or not fully functional. These differences where found and fixed for the QNX port of ATFTP.

- QNX does not have the `getopt_long` function used to parse arguments that are passed to an application as standard.

The functionality to set the number of timeouts before the file transfer is aborted was fixed in the code in the original ATFTP client. A command line option was added to set this value in the QNX port.

The TFTP and NFS clients are both good candidates for the application layer protocol used to transfer files between the satellite and ground stations. NFS has the advantage that a simpler design could be created because the contents of directories can be seen and files are copied more easily.

The choice of protocol in the initial stages of the project design could have severe implications later on in the project. It was decided to design the e-mail system to work with both the TFTP and NFS protocols from the beginning of the project design. This decision allows the e-mail system the option to use the protocol that is more efficient in the real world environment at a later stage.

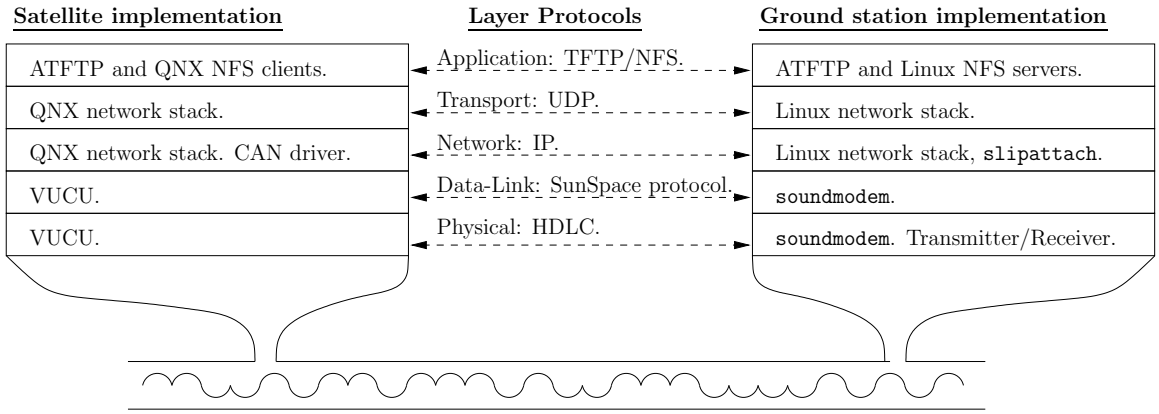

Figure 3.4: *Summary of the e-mail system OSI layer structure for the satellite and ground stations.*

The complete OSI layer design for the ground station has now been described and a summary of the design can be seen in figure 3.4. Thus it is now possible to communicate transparently between the satellite and the ground station. Files can be transferred using TFTP or NFS and this is the final step that is needed to implement the e-mail system. The next chapter will describe how the e-mail system itself was designed.

Chapter 4

E-mail System Design

In this chapter the design of the e-mail system will be described. The first part of the chapter will just give a few definitions of administration directories and files that are used in the e-mail system to enable an easier understanding of the system when the design is shown in section 4.3. The term upload will be used to describe when a file gets transferred from a ground station to the satellite. The term download will be used to describe when a file gets transferred from the satellite to the ground station.

4.1 Components of the System

4.1.1 Ground Station

The e-mail domain is used to identify ground stations in the system. Table 4.1 shows the definition of the domain structure used in this text.

Table 4.1: *Domain and sub-domain definition. stb.sumbandilasat.co.za is used as an example to explain the definitions.*

Complete domain	
Sub-domain	Domain
stb	sumbandilast.co.za

Each ground station has a specific sub-domain which is a unique key to describe the ground station. For example the complete domains cpt.sumbandilast.co.za, blm.sumbandilast.co.za and jhb.sumbandilast.co.za may be used to describe the ground stations found at Cape Town, Bloemfontein and Johannesburg respectively.

The ground station can have many users, for example test0@cpt.sumbandilast.co.za and test1@cpt.sumbandilast.co.za. Each ground station also has a unique IP address for the satellite ground station network. The ground station has the following directories to keep track of all the e-mails:

- `Outbox`
  This is the outbox where all e-mails to non-local users are placed before they are uploaded to the satellite.

- `Inbox`
  This is where all e-mails downloaded from the satellite are placed before they are moved by the ground station software to the correct user inboxes.

- `User Inboxes`
  The e-mails for a specific user received from the satellite or another local user are placed in this directory.

- `Default User Inbox`
  This is where all e-mails received at a ground station with the correct domain name and incorrect user name are placed. For example if an e-mail is sent to test2@cpt.sumbandilasat.co.za and the user does not exist on the ground station 'cpt' then the e-mail will be placed in this inbox.

4.1.2 Satellite

The satellite does not keep track of specific users on a ground station. The satellite has the following directory structure to administer the e-mails and ground stations that exist on the e-mail system network:

- `Global Outbox`
  This is the global outbox for e-mails that have been uploaded to the satellite but are not being sent to a user on the e-mail system network. These types of e-mails are e-mails that are not destined for the sumbandilasat.co.ca domain for the example being used in this chapter.

- `Ground Station Outbox`
  This is the outbox where all e-mails for a specific ground station are placed once they have been uploaded to the satellite and are ready to be downloaded to the ground station. E-mails are downloaded from here to the `Inbox` on the ground station. This directory is simply named after the complete domain of the ground station.

- `Inbox`
  The global inbox where e-mails are placed once they have been uploaded from a ground station to the satellite and before they are moved to the correct `Ground Station Outbox`.

- `Administration`
  The directory where all administration files described in the next section are stored.

4.1.3 Administration Files

The system is designed to work on TFTP. TFTP is unable to list the contents of remote directories. Thus file lists are needed to keep track of files that must be uploaded or downloaded. The different files used for these lists are now described and the files used to acknowledge uploads and downloads are also described.

- `Upload List`
  This file is maintained by the ground station. It contains the list of all the files that must be uploaded to the satellite. Files are removed from this list once the satellite has uploaded the file and acknowledged that the file has been uploaded.

- `Upload Ack List`
  This is a file that the satellite maintains to record which files have been uploaded already. The file is used to make sure that the satellite does not upload a file twice.

- `Upload File Ack`
  This is sent from the satellite to the ground station to let the ground station know that a file has been uploaded. An `Upload File Ack` is sent to the ground station to acknowledge the reception of a file for each file individually.

- `Download List`
  This is the file on the satellite that contains the list of all the files that must be downloaded. Only the satellite is interested in this file and the ground station never sees this file.

- `Download Ack List`
  Once a file is downloaded to the ground station a ground station adds the file to this list. It contains the list of all files that have been downloaded to the ground station. The satellite uploads this file to see which files have been downloaded successfully.

- `Download OK`
  The satellite sends this file to the ground station once it has uploaded the `Download Ack List` to let the ground station know that the `Download Ack List` has been uploaded. This lets the ground station know that it can remove all the administration files for the downloaded files.

4.2 Design Choices

The e-mail system was designed to be able to transfer any arbitrary file. The goal was to make the satellite software to be as simple as possible. The satellite does not do any parsing of e-mails. A simple file naming strategy is used to retrieve the destination address of a file.

There are two types of ground stations used for this system. Normal ground stations do not have any access to the Internet other than communicating through the satellite network.

Gateway ground stations have access to the Internet and act as gateways between the satellite network and the greater Internet.

The e-mail system is designed to be as reliable as possible. If the link fails unexpectedly at any point in the transfer process or the software on the satellite is switched off by the satellite control, the system must be able to recover from the event.

For every file that is uploaded or downloaded the file is only removed from the system once the upload or download has been acknowledged as successful. Thus the upload or download of a file is reliable.

E-mail clients and user applications can be used to ensure end-point to end-point delivery of the message. The e-mail system only allows the ground station to be able to determine when a file has been uploaded successfully.

The e-mail system was also designed to have a priority system. Each ground station has a priority assigned to it and each e-mail has a priority assigned to it. The ground station priority takes precedence. This can be used to ensure that gateway ground stations get more service time which will probably be necessary because gateway ground stations will receive more traffic than other ground stations.

The e-mail priority can be used to ensure that certain users have different priorities at a ground station to make sure that the important users get serviced first for that ground station.

Now that a background to the terminology used in this chapter has been given, a description of the e-mail system can be described in detail.

4.3 Flow Charts of the Different Components

4.3.1 Download

Figure 4.1 and figure 4.2 show the flow charts that describe how the downloading of files is implemented on the satellite and ground station respectively. The flow chart in figure 4.1 is executed when a ground station is selected to be serviced by the satellite. The flow chart in figure 4.2 is executed regularly by a ground station.

In step 1 in figure 4.1 the Download List is created from the files in the specific ground stations `Outbox` or `Global Outbox`. For a gateway ground station this will be created from the files in the `Global Outbox` and for a normal ground station it will be created from the files in the ground station's specific `Outbox`.

Step 3 is only executed if there are new files to download. In step 3 three attempts to retrieve the `Download Ack List` are executed to give the ground station a fair chance of being serviced by the satellite if the link to the ground station is not particularly good. Thus if a ground station is found in a region where physical attributes of the region produce a bad link compared to other ground stations, the ground station is still serviced by the satellite.

If the `Download Ack List` is not retrieved successfully the satellite then exits the flow chart and services the next ground station. If the `Download Ack List` is retrieved then step

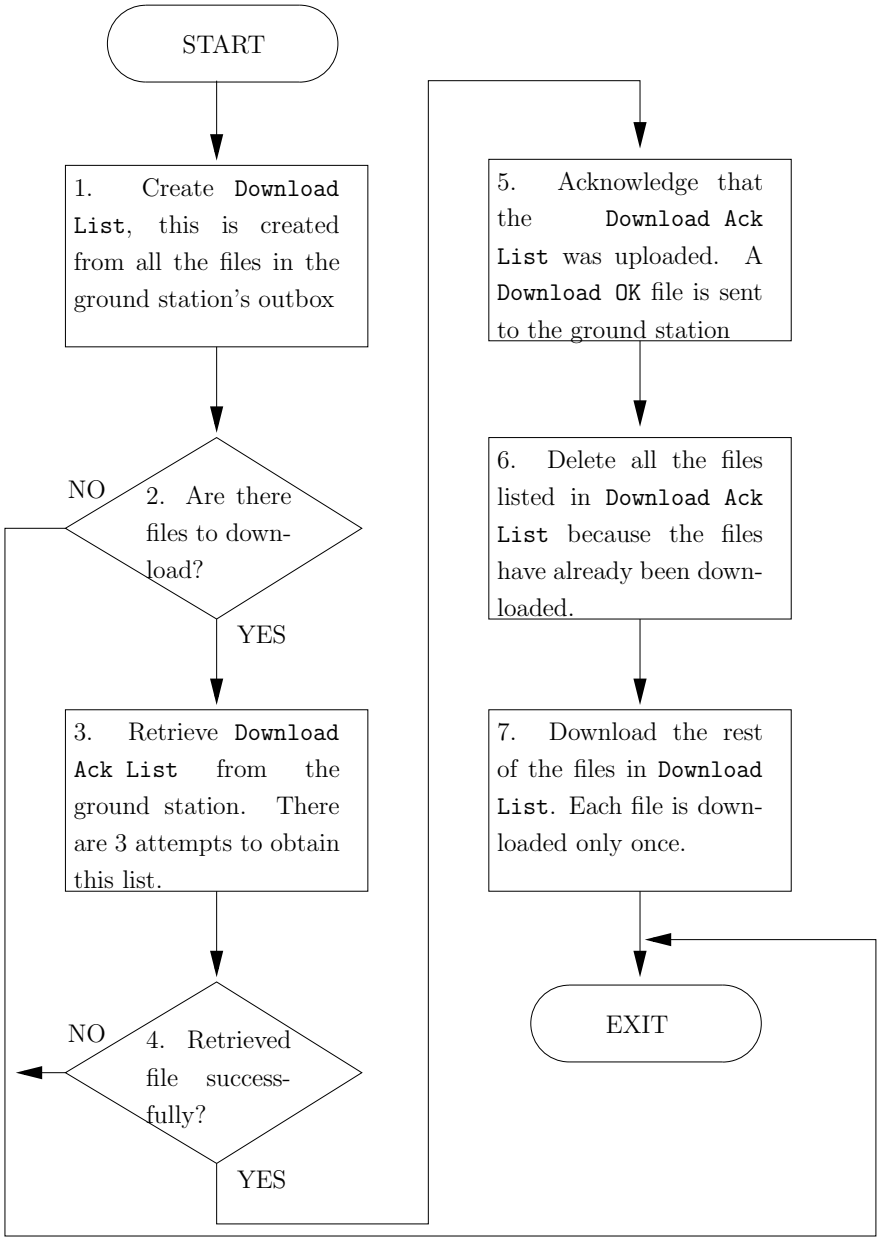

Figure 4.1: *The satellite download flow chart. This flow chart is executed whenever a ground station is being serviced by the satellite OBC.*

5 is executed. The `Download OK` file is then transmitted to the ground station to let the ground station know that the `Download Ack List` had been uploaded successfully.

Only one attempt is made to download the `Download OK` file. If this file is not downloaded successfully it does not influence the rest of the flow chart significantly. If the ground station receives the `Download OK` file then step 2 in figure 4.2 is executed. The reason why the `Download Ack List` is deleted in step 2 in figure 4.2 once the `Download OK` file is received is because then the ground station knows that the satellite has uploaded the `Download Ack List` successfully. Thus the files in the list do not have to be acknowledged anymore.

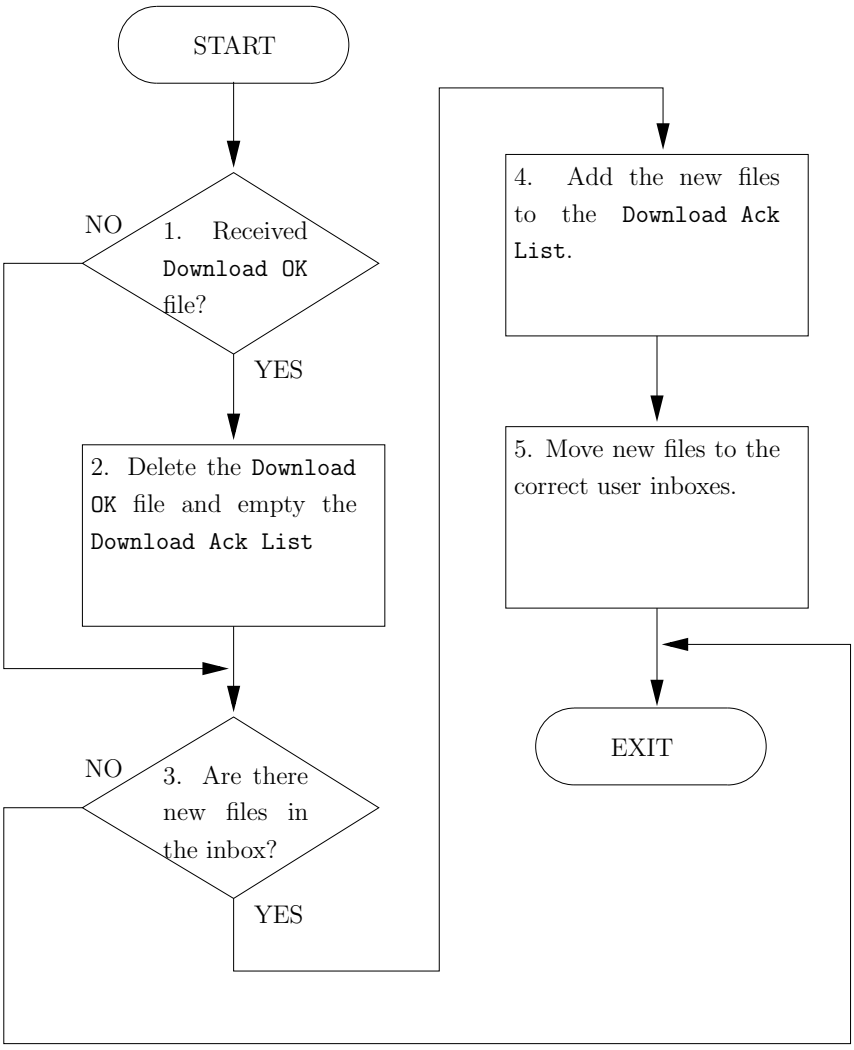

Figure 4.2: *The ground station download flow chart. This flow chart is executed whenever a file is received on a ground station by the ground station software.*

If the `Download OK` was transmitted to the ground station by the satellite and the ground station does not receive it then all that happens is the next time the satellite services the ground station it will re-upload the `Download Ack List` with the old entries still present in the list.

After step 6 in figure 4.1 the satellite then starts to download the files (step 7, figure 4.1). When the ground station receives a new file in step 3 of figure 4.2 it simply adds this file to the `Download Ack List` (step 4, figure 4.2) and then moves the file to the correct ground station `User Inbox` or the `Default User Inbox` (step 5, figure 4.2). If the ground station is a gateway ground station then the information will be forwarded to the greater Internet if necessary.

The downloading of e-mails has now been described and a full transactional interface is provided. Files are only deleted from the satellite once the ground station has acknowledged

that it has received the file, thus a reliable down-link is provided.

4.3.2 Upload

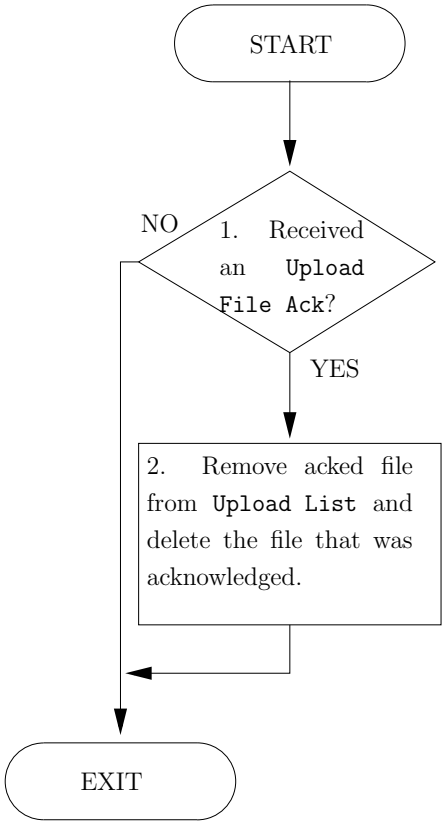

Figure 4.3: *The ground station upload flow chart.*

Figure 4.3 shows the flow-chart that describes how the ground station software implements the uploading of files to the satellite. This file is executed regularly by the ground station. It will be executed approximately once a second. If a ground station receives an acknowledgement for a file from the satellite to confirm that the satellite has uploaded the file successfully then the file is deleted on the ground station and the file is removed from the `Upload List`.

The flow chart on the satellite shown in figure 4.4 is more complicated than the ground station upload flow chart and will now be explained. The flow chart is executed when a ground station is serviced by the satellite. In step 1 the satellite tries to retrieve the `Upload List` from the ground station and it is repeated three times for the same reasons described in section 4.3.1 in the download flow chart.

Once the `Upload List` has been received, the satellite needs to determine which e-mails have already been uploaded to prevent duplicate uploading of e-mails. The file `Upload Ack List` on the satellite is required to record this information because once a file has been uploaded to the satellite it is moved to a different mailbox on the satellite. For this reason

it is impossible for the satellite to create the `Upload Ack List` from information on the satellite.

The only problem that can occur if for some unknown reason the `Upload Ack List` is removed on the satellite, is that the files that were in the list will potentially be uploaded twice.

The `Upload Ack List` is created when a new `Upload List` is uploaded from the ground station as shown in step 4. The new `Upload List` that was uploaded then has all the entries in the `Upload Ack List` removed from it to make sure that a file is not uploaded twice (step 3).

If there are still files in the `Upload Ack List`, it means that the acknowledgements for the files in the list where not received by the ground station. The ground station has thus not removed the files from its Upload List. The acknowledgements for the files in the `Upload Ack List` are then resent to the ground station (step 5, figure 4.4) so that the ground station removes the entries from its `Upload List` (step 2, figure 4.3).

For all the files in the new `Upload List` calculated in step 3 of figure 4.4 the files are uploaded. If the file is uploaded correctly then an `Upload File Ack` is sent to the ground station to acknowledge the correct uploading of the file. This causes step 2 in figure 4.3 to be executed.

If the file was not uploaded correctly then no other attempt is made to upload the file in the current session. The file is simply deleted on the satellite (step 9, figure 4.4). Once all the files have been attempted to be uploaded, the correctly uploaded files are moved to the correct mailboxes on the satellite (step 11, figure 4.4). The flow chart then exits and the next ground station is selected to be serviced.

The files that were not uploaded successfully will be uploaded the next time the ground station gets serviced by the satellite. The file on the ground station is only deleted if the satellite has acknowledged that the file has been uploaded to the satellite. Thus a reliable uploading of files is guaranteed.

The uploading and downloading of e-mails has now been described. The next section provides an example of the uploading of a file and downloading of a file to illustrate how the system works in practice.

4.4 Typical File Transfer Sequences

An example of an upload and download of an e-mail is now shown to help explain how the system works. Figure 4.5 shows the sequence of events that occur when an e-mail, called E-mail 1, gets uploaded to the satellite. In this example a user at ground station `Blm` sends E-mail 1 to User 2 at ground station `Cpt`.

The user is not on the local ground station thus it must be uploaded to the satellite. The e-mail is placed in the `Outbox` and added to the `Upload List`. The actions in the dashed block 1 in figure 4.5 illustrate how this is performed.

The ground station now has to be serviced by the satellite and the actions that occur when this happens is shown in dashed block 2 in figure 4.5. The actions in dashed block 2 illustrates what happens in the flow-chart in figure 4.4. The e-mail is uploaded by the satellite and the acknowledgement of this upload is sent back to the ground station.

When the satellite services ground station `Blm` the next time round it will upload the `Upload List` and see that there are no new files to upload to the satellite because `Blm` has removed E-mail 1 from the `Upload List`. E-mail 1 will be removed from the `Upload Ack List` on the satellite.

The acknowledgement that E-mail 1 has been uploaded causes dashed block 3 in figure 4.5 to be executed. This dashed block illustrates what happens in the flow-chart in figure 4.3.

Now the e-mail has been uploaded from the ground station `Blm`. The satellite will then have to download the file to `Cpt` when `Cpt` gets serviced next. Figure 4.6 illustrates what happens when `Cpt` gets serviced.

Dashed block 1 in figure 4.6 performs the action in step 1 and the test in step 2 in figure 4.1. There are e-mails to download because E-mail 1 has been placed in `Cpt`'s outbox. Thus the `Download Ack List` is retrieved from the ground station (step 3, figure 4.1). Dashed block 2 in figure 4.6 performs the steps 4, 5 and 7 in figure 4.1. No files are deleted in step 6 in figure 4.1 because there where no other files on the satellite.

`Cpt` has thus received the E-mail 1 from the satellite and this causes the sequence of events in dashed block 3 in figure 4.6 to be executed on the ground station. The steps 1, 2, 3, 4 and 5 in figure 4.2 are then executed because an e-mail was received and the `Download OK` file was received. User 2 on ground station `Cpt` has now received an e-mail from ground station `Blm`.

The next time `Cpt` gets serviced by the satellite dashed block 1 will again be performed in figure 4.6. Dashed block 4 is then performed. The `Download Ack List` will be retrieved from `Cpt`. The `Download Ack List` contains the E-mail 1 in the list so the new calculated `Download List` on the satellite will no longer have the entry in it. Thus E-mail 1 is not downloaded again and only the `Download OK` file is downloaded to the ground station. The file on the satellite is then deleted (step 6, figure 4.1). `Cpt` receives the `Download OK` file and the steps 1 and 2 are performed in figure 4.2 on the ground station.

The e-mail has now been cleaned from all lists on the satellite and the ground station and the complete uploading and downloading of a file is complete.

This chapter has explained how the e-mail system was designed and how a reliable transfer of files is achieved. The next chapter explains how this was implemented on the OBC hardware and the ground station desktop computers.

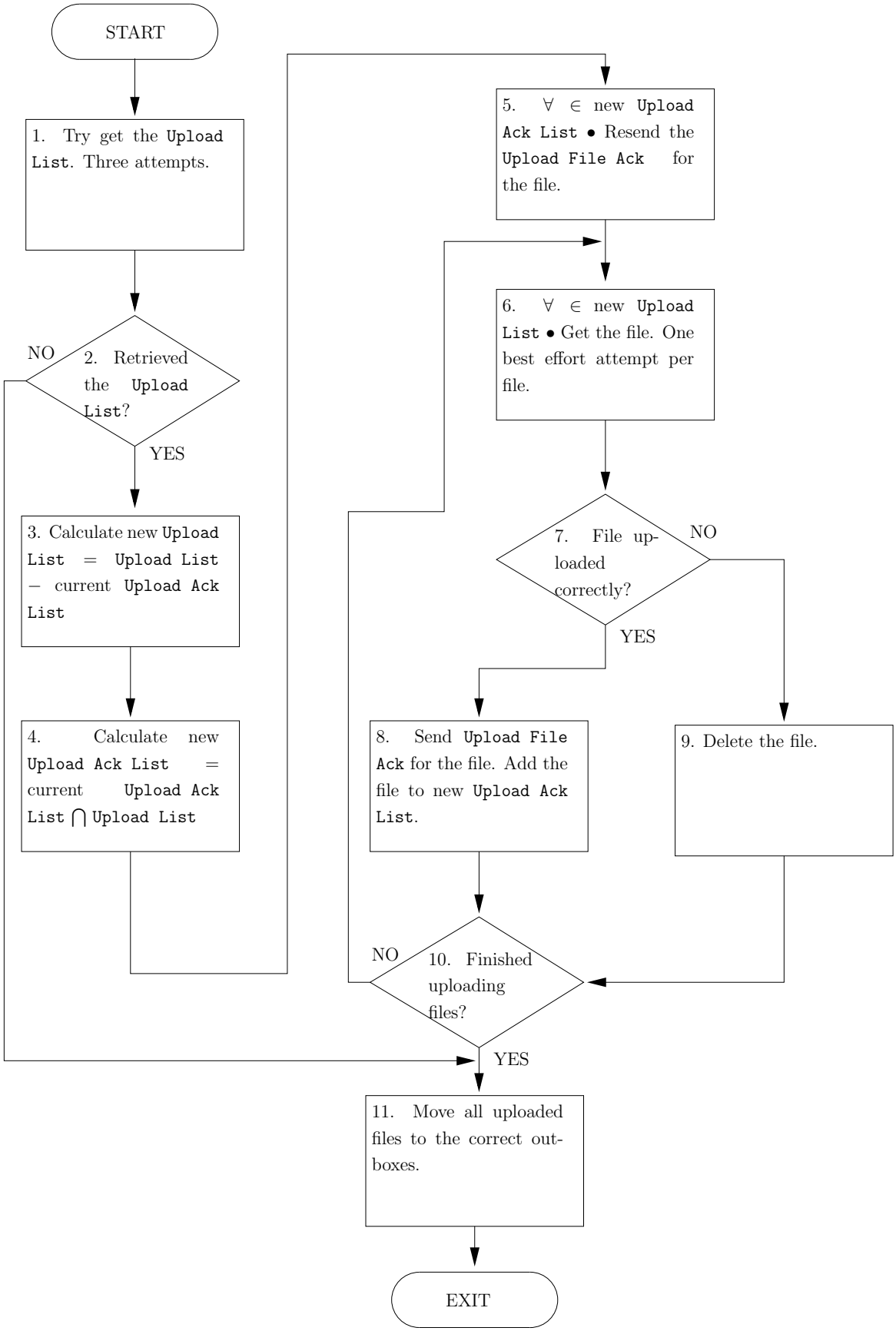

Figure 4.4: *The satellite upload flow chart.*

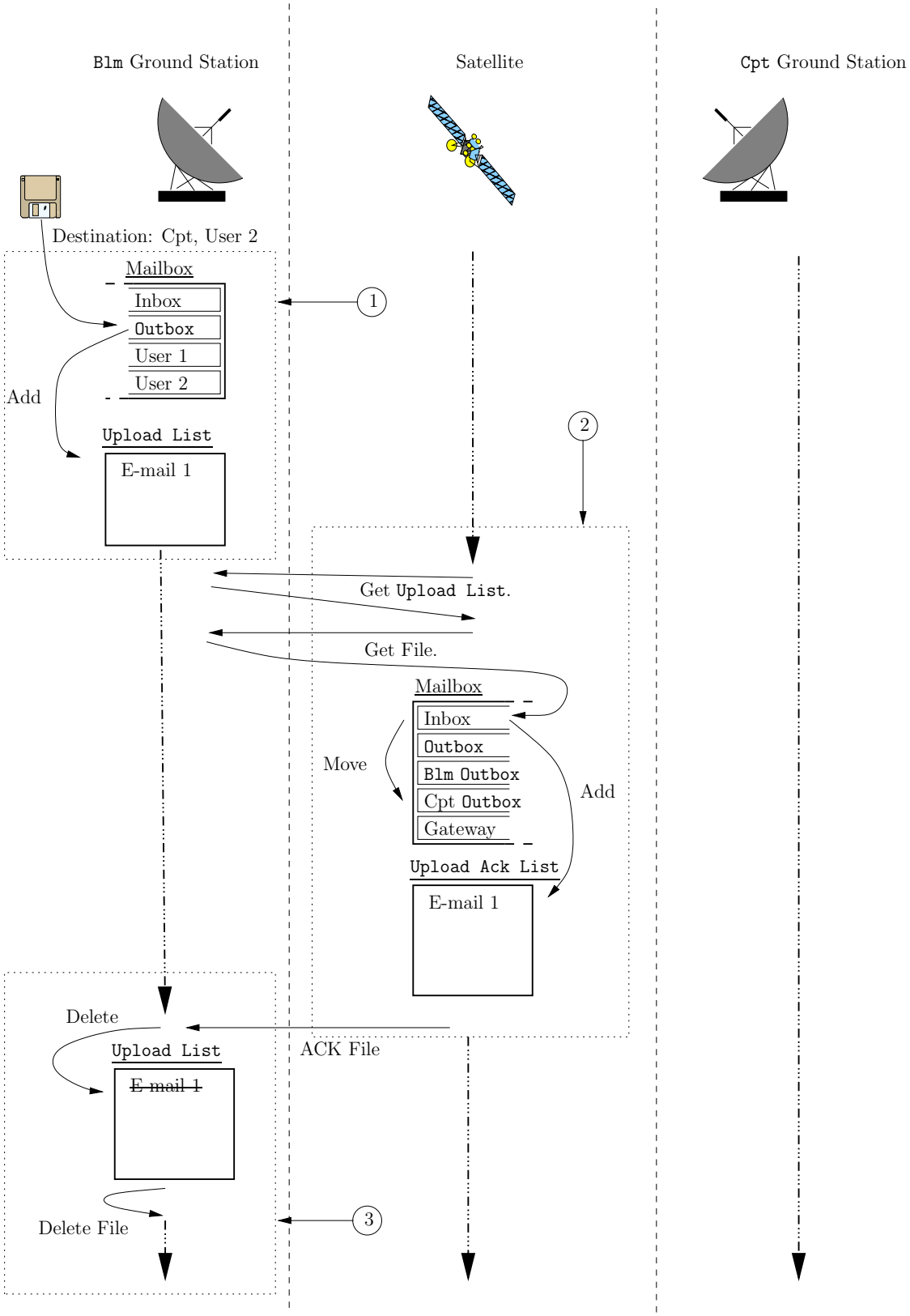

Figure 4.5: *E-mail transfer upload example.*

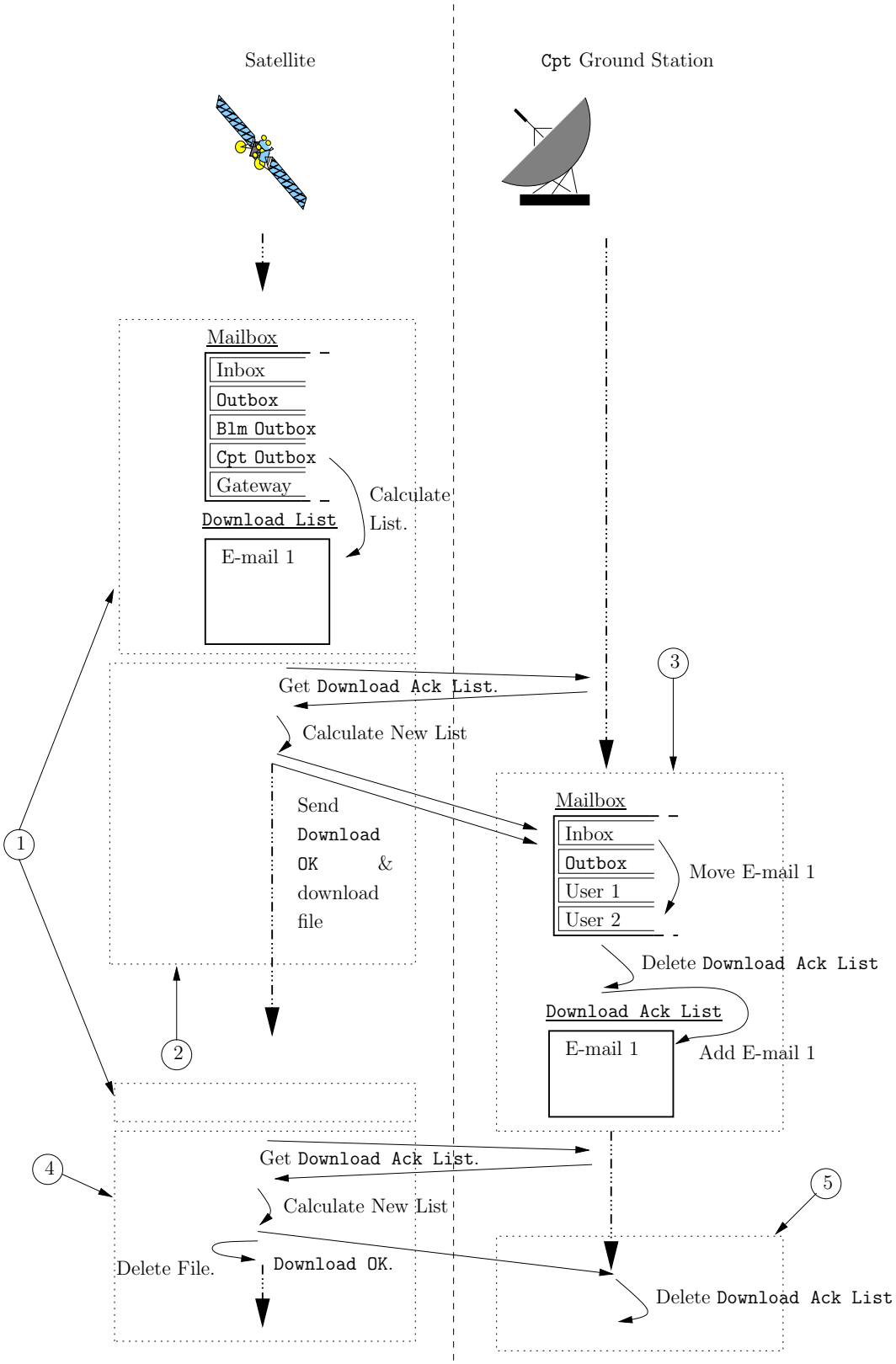

Figure 4.6: *E-mail transfer download example.*

Chapter 5

E-mail System Implementation

The implementation of the design in the previous chapter will be described in this chapter. The following ideas where kept in mind when implementing the design:

1. The code on the satellite must be kept as simple as possible.
2. The code must be split up into independent components.
3. Create a system that is easy to maintain, which the previous point helps to achieve.
4. Try to use as many existing applications and tools as possible to prevent reinventing the wheel.
5. Add some security to the system to ensure that no malicious users can easily gain access to the system.
6. When accessing the link try to use the link as effectively as possible.
7. The satellite must poll ground stations and the ground stations must not use the link unless they have been given access to the link by the satellite.

This chapter is going to describe how these points where achieved. Chapter 4 described the design of the software used to transfer files between end-users. There are many more components of the system, such as administration scripts, that are not described in chapter 4 because they are not an integral part of the e-mail system. These additional scripts will be described in this chapter.

5.1 Overview

There are a few concepts that are common to both the satellite software and the ground station software. These will be described in this section.

5.1.1 File Integrity and Security

The transfer of a file between the ground station and the satellite uses either the NFS protocol or the TFTP protocol to achieve the transfer. The satellite and ground station need to know that when a file is transferred between the satellite and the ground station it is firstly completed correctly and secondly that the file does indeed come from the correct ground station. Both of these points are achieved by transferring a Secure Hash Algorithm version 1 (SHA-1) check sum of the file whenever a file is transferred between the satellite and a ground station or vice versa. The SHA-1 is a secure hashing algorithm that takes a stream of bytes of arbitrary length and converts it into an unique fingerprint or digest that is unlikely to be created from any other stream of bytes [6].

The SHA-1 sum of a file is created using the following command in a Korn or Bash Shell:

```
cat in_file signature_file | hashsum sha1 > in_file.hash
```

This command outputs the contents of the file 'in_file' and 'signature_file', pipes the data to a tool called 'hashsum' [5] that calculates the SHA-1 and save the result to the file 'in_file.hash'.

The hash file, 'in_file.hash', is unique for a given file 'in_file'. Thus if a file is transferred incorrectly then the receiving application will be able to tell if the file got corrupted during transmission or uploaded incompletely.

The 'in_file.hash' contains a hash (calculated using SHA-1) that is calculated over the contents of both the file 'in_file' and 'signature_file'. Thus it is impossible to create the correct hash file unless you know what the contents of the 'signature_file' is. So then it is possible to have an unique signature file that is only known by the satellite and a specific ground station. The satellite is then able to calculate hash's that are unique to that ground station and receive e-mails from the ground station only if the ground station uses the correct signature file to calculate its hash.

The use of the hash and signature file ensures that all files are uploaded and downloaded correctly. The use of the signature file also makes it difficult for a malicious user to gain access to the e-mail system unless he is able to determine the signature file for a ground station. Thus a level of security is added to the system.

5.1.2 TFTP and NFS setup

All the ground stations and the satellite share the same channel. Thus it is important that only one ground station is communicating with the satellite at one time, i.e. the rest of the ground stations must not access the channel when the satellite is communicating with a specific ground station.

In section 3.3 it was shown that either TFTP or NFS would be good choices for the protocols used to transfer files between the ground station and the satellite. In the implementation of the e-mail system it was decided that the satellite should run the NFS or TFTP clients while the ground stations should run the servers for these protocols.

The reasons for this is as follows:

- The satellite is in control. It can initiate the connection or destroy the connection.
- The ground station is unable to access the channel unless the satellite first initiates a file transfer with it.
- By carefully choosing the timeouts and retries that are used for retransmission of lost packets in the TFTP and NFS protocol, one can know with certainty when a ground station will no longer be accessing the channel.

5.1.3 List File Formats

The different lists for the files also have a specific format that is shown in table 5.1.

The "\t" used in the `Upload List` is the horizontal tablature (HT) ASCII character. The HT character was used for the `Upload List` format because it is not possible to have this character in a file name or in an e-mail address. Splitting the line into different fields by using the HT character as the delimiter will work under all situations.

The "\n" is the newline character which on UNIX is the line feed (LF) ASCII character. The LF is the character used for a new line right throughout the e-mail system code.

Table 5.1: *File structure of the different list files and acknowledgement files.*

`Upload List`	<File name> \t<Destination e-mail> \t<Source e-mail> \n
`Upload Ack List`	Same as the Upload List
`Upload Ack`	Same as the Upload List
`Download Ack List`	File name\n
`Download Ack`	File name\n

5.2 Satellite

The satellite software has three different independent components that will be discussed in this section. The programming language that was used for the component is first discussed and the functionality of the software is then discussed.

5.2.1 Administration Software

The administration software is written using Korn Shell scripts. The e-mail system software described in section 5.2.3 also uses the KSH scripts. The reasons for using KSH for these two components is now discussed.

- Korn Shell scripts are very useful when calling standard Unix commands. The nature of the administrative software and the e-mail system makes it necessary to move files

around the files system frequently and to call commands such as “hashsum”. Doing this sort of action from C, for example, is a lot more cumbersome than simply running the command in the script.

- Korn Shell is the default shell used on QNX. Korn Shell is very similar to the Bash Shell. Thus using the Korn Shell is not difficult to learn if the developer is accustomed to the Linux operating system because the Bash shell is the standard shell on Linux.

- To use the QNX C compiler to compile software for the QNX operating system a developer has to purchase a software license. This license lasts for one year and then the developer has to renew the license. To develop KSH scripts does not require this license so the system can be maintained without licensing costs for the lifetime of the satellite.

The use of the Korn Shell is not optimal in performance because it is an interpreted language which is slower that a compiled language. The benefits of using the Korn Shell outweighed this negative aspect of the shell and the Korn Shell was chosen as the language for the administration software.

The administration software consists of two KSH scripts. These scripts are designed to be generic so that they can be used for many of the administration tasks. The scripts' names are listed below and the functionality that they provide are then described:

- **MinimumCommand <IP address> <ground station file> [satellite file]**
  This script takes two compulsory arguments and one optional argument. The IP address in argument one is specified using the number-dot format for IP addresses, for example ‘10.0.0.1’. The script sends a request to the default gateway ground station to upload the file specified in argument two. The script then tries to upload the file.

  If argument three is not specified then the file that was uploaded is executed and assumed to be a KSH script. If argument three is specified then the uploaded file is copied to the path that the argument specifies. The script is designed to work under the worst possible situations.

  All files that are transferred using this command are encrypted using the Blowfish encryption algorithm [2]. The ‘encrypt’ [5] command performs the encryption and decryption of the files. These files are encrypted because the files might contain critical upgrade scripts for example, which should not be viewed by unknown parties.

- **DownloadLogCommand <IP>**
  This command simply tries to download the logs from the satellite to the ground station whose IP is specified as argument 1.

MinimumCommand and DownloadLogCommand are implemented to try work with the least amount of other resources being used. Thus they do not source other scripts that are not

absolutely necessary to their operation. By source it is meant that they do not use any functionality that is found in another script.

The MinimumCommand can be used to upload any arbitrary KSH script and execute it or it can upload any file to the satellite file system. The administrator can thus use this command to add new ground stations to the system. It can also be used to update software on the satellite.

The DownloadLogCommand is just a helper command; the MinimumCommand could achieve the same functionality by uploading a script that then downloads the logs.

5.2.2 Ground Station Selection Software

The ground station selection software is used to manage the servicing of the different ground stations. The software is written in the C programming language. The reasons for writing this software in C is described next:

- The QNX operating system is written in C thus the C run-time libraries are loaded into memory as default. Writing the software in C does not increase the memory usage of the user applications on the OBC dramatically because of this fact.
- This piece of software does not interact with the file system as frequently as the other parts of the e-mail system found on the satellite. Thus the benefits provided by the Korn Shell in this regard are not as important.
- This piece of software only manages the system and thus the amount of time spent executing this code must be minimised because the satellite does not utilise the link while executing this code. C can be a very efficient language and the time spent executing the ground station selection software is kept to a minimum by using C for this software.
- The process monitor software developed by SunSpace has a specific method of starting a process and stopping a process. The ground station selection software is started by the process monitor and thus needs to conform to this standard. Sunspace provides C libraries to allow the ground station selection software to communicate with the process monitor in the standard way.

The selection of the ground stations was implemented by Retief Gerber and the initial design of the software was implemented by the author. The selection of the ground stations will be briefly described for clarity:

- A *hosts.current* file contains a list of all the ground stations that are enabled on the system.
- The selection software creates a copy of the list in the *hosts.current* file and stores the list in a file called *waiting.current*. The software randomly services a ground station

in the *waiting.current* file's list. The serviced ground station is removed from the *waiting.current* list when it is finished being serviced. When the list is empty the process repeats itself. This creates a scheduling process whereby a ground station is selected randomly but every ground station gets a fair amount of services.

- Ground stations can have different priorities. To enable a priority system in the selection process the ground stations with higher priorities have more entries in the *waiting.current* list. Thus the ground stations with the higher priority will be serviced more regularly than the other ground stations.

- Every time a ground station is selected the lists are updated in a manner so that if the program exits unexpectedly (e.g. killed by the process monitor) it is able to recover to the state where it was prior to the exit. The fairness of the selection process is thus maintained.

The flow chart of the design of the ground station selection software is shown in figure 5.1. In steps 1, 2 and 4 in figure 5.1 the KSH scripts are called from the control software.

This abstracts the complexities of the system away from the control software. The control software is thus only involved in the selection of the ground stations. The implementation of the system in this manner creates a system which can easily be updated by simply updating the scripts that are called in steps 1,2 and 4 in figure 5.1. This creates a system that is easy to maintain.

5.2.3 E-mail System Software

The scripts mentioned in the figure 5.1 implements the e-mail design described in chapter 4. A description of the functionality of each of the files and other utility scripts is now given:

- **Global.ksh**
  This script sets all the global variables that are shared between the different scripts. All the scripts except MinimumCommand and DownloadLogCommand source this script to get hold of the global variables.

- **copy_to_mailbox.ksh**
  This script copies all the e-mails in the satellite inbox to the relevant outboxes of the ground station.

- **InitCommand**
  This script performs the following actions:

  - Checks that none of the scripts on the satellite have been corrupted or are missing. Tries to upload missing or corrupted files using the MinimumCommand. Files will only become corrupted or missing on the satellite if an error occurs with the file system.

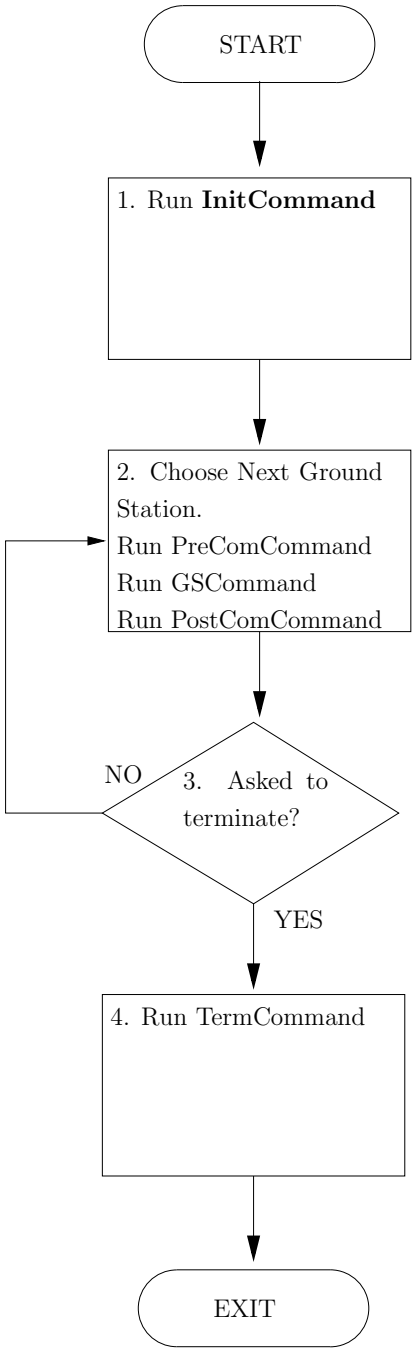

Figure 5.1: *The control software flow chart.*

- Then checks that all the compulsory directories and files exist and creates them if necessary
- Deletes all the files in all the ground stations' respective `Download Ack Lists`. This is repeated here so that if there are many files to delete this action can be executed before the satellite communication window falls over the area where ground stations can be accessed. Thus when the satellite is in the communications

window it will use the communication time better.

- Checks the size of the output and logging files and if they exceed a user-defined maximum file size, compresses the file using the gzip utility and rotates the logs. The scripts creates the files log.gz.0, log.gz.1 etc.

- **PreComCommand <IP address> <ground station name> <is gateway>**
  The IP address is specified in number-dot format. The 'ground station name' argument is the sub-domain of the domain for the ground station, for example 'stb'. The 'is gateway' argument is a 0 or a 1 to specify if the ground station is a normal ground station or a gateway ground station respectively.

  The script name PreComCommand stands for the pre-communication command. This script performs the following actions:

  - Checks that any specific compulsory directories and files to this ground station exist and then creates them if necessary.
  - Checks if any scripts have been uploaded to the satellite and need to be executed. It then executes them and deletes the script after that. This action is placed in the PreComCommand because it is always executed between the servicing of different ground stations on the satellite.

- **GSCommand <IP> <ground station name> <is gateway>**
  The arguments are specified in the same manner as for the PreComCommand. The script name GSCommand stands for the ground station command.

  This script implements the satellite download flow chart shown in figure 4.1 and the satellite upload flow chart shown in figure 4.4. GSCommand first tries to download files and then tries to upload files. This ensures that e-mails are first moved off the satellite before new e-mails are uploaded which helps to control the number of e-mails that are present on the satellite at one time.

  The script calls the copy_to_mailbox.ksh script at the beginning and the end of the script to move e-mails to the correct outboxes. The copy_to_mailbox.ksh script is only called if new e-mails have been uploaded onto the satellite since the last time the script was called.

  GSCommand is also designed to use different transfer protocols for the transferring of e-mails. The transfer method can be changed by the satellite administrator. The different options are listed below. The order of the list specifies the order of precedence used to determine which protocol is used.

  - **TFTP**
    The default QNX TFTP client is used. This is the default option.

  - **NFS**
    The QNX fs-nfs3 client is used for the transfer method. This NFS version 3 client is used if the file /var/spool/mail/admin/nfs exists.
  - **ATFTP**
    The cross-compiled Linux ATFTP client is used. This client is used if the file /var/spool/mail/admin/atftp_options exists. The file can be created using the following Korn Shell command for example:

```
1   echo "atftp -t 2 -T 2 -R 3 -b 512 " > \
2     /var/spool/mail/admin/atftp_options
```

    The atftp_options example above causes atftp to be called with a ground station and satellite retry timeout of 2 seconds. The amount of retries is set to 3 and the packet size is set to 512 bytes.

- **PostComCommand <IP> <ground station name> <is gateway>**
  The arguments are specified in the same manner as the PreComCommand. The script name stands for post-communication command.

  This script makes sure that all the tftp, atftp and fs-nfs3 processes have exited correctly. The processes are terminated if they have not exited.

- **TermCommand**
  The current version of the TermCommand has the same functionality as the PostCom-Command.

5.3 Ground Station

The implementation of the ground station software is simpler than the satellite software. The reasons for this are as follows:

- Resources are not restricted. The processing power of even a low-end desktop computer will still be substantially higher than that of the OBC.
- The ground stations use the Linux operating system which allows the developer to use any programming language of his choice from the multitude of software tools available on Linux.

The Python programming language was chosen as the language to implement all the e-mail system ground station scripts. The reason for this is as follows:

- Python is a very easy language to learn. The on-line community is strong and the documentation for the programming language is of a high quality.

- Python interacts with the file system in a straightforward manner. The ground station software has to move files around frequently, check for new files and interact with the file system in general. By choosing a language that performs these operations easily, a simpler program can be developed.
- Python has some very powerful high-level data-structures that make operations on, for example lists of files simple.
- Python has a good unit-testing testing framework called PyUnit. The use of this framework will be described in more detail in chapter 6.

The ground station has three different components in the system. These are now discussed in more detail.

5.3.1 Administration Scripts

- **sun_node_admin.py**
  This script manages the system on the ground station. It performs the following actions:
  - Add and remove local users of the e-mail system on the ground station.
  - It can create the default configuration file used to setup the e-mail system on the ground station.
- **sun_satellite_admin.py**
  This script manages software on the satellite. It performs the following actions:
  - Uploads files onto the satellite and can perform software updates of the satellite software.
  - Download logs from the satellite.
  - Upload and execute scripts on the satellite.
  - Manages ground stations that the satellite services.

5.3.2 User Interface

Two methods for users to access the system were implemented.

There is a script-based system that uses the scripts sun_sendmail.py and sun_fetchmail.py to place mail into the system and get mail from the system respectively. These scripts will most likely be used for testing the system and for applications that use the system to transfer files and not specifically transfer e-mails.

There is also an e-mail client system that is used to place mail into the system and get mail from the system. E-mails are placed into the system using the script sun_stmpserver.py which implements a Simple Mail Transfer Protocol (SMTP) server in Python. Albert Strasheim

was involved in the development of this script. The user can run any normal e-mail client such as Mozilla-Thunderbird or Outlook to access the SMTP server. These e-mail clients must be configured to use the ground station as the SMTP server.

E-mails are retrieved from the system by using the Internet Message Access Protocol (IMAP) server Dovecot. Dovecot is an IMAP and Post Office Protocol (POP) server for Linux. Only the IMAP capabilities of Dovecot is used. The user can now also run any normal e-mail client to get e-mails from the system if they configure the client to use the ground station as the IMAP server.

Dovecot can be configured to use the MailDir format for user mail boxes. The MailDir mail box format is explained by showing the directory structure used by Dovecot for a user test0@blm.sumbandilasat.co.za:

```
1  >> ls -1 /var/spool/mail/test0@blm.sumbandi\-lasat.co.za/
2  cur/
3  dovecot.index
4  dovecot.index.cache
5  dovecot.index.log
6  dovecot-uidlist
7  new/
8  tmp/
```

The Linux command in line 1 lists the contents of the user test0@blm.sumbandilasat.co.za's inbox. There are 3 sub-directories in this directory, `cur`, `new` and `tmp`. The e-mail system simply copies all newly received e-mails into the directory `new`. The e-mail will then automatically be detected by Dovecot and the user will be able to retrieve it using their e-mail client. The e-mail's name is irrelevant to the Dovecot server. The rest of the files are used by Dovecot for book-keeping purposes and are of no interest to the e-mail system.

5.3.3 E-mail System Scripts

The e-mail system flow charts were split into two scripts, unlike the satellite script GSCommand that implemented all the functionality in a single script. The scripts sun_monitor_mailbox_download.py and sun_monitor_mailbox_upload.py implement the flow charts shown in figure 4.2 and 4.3 respectively. The reasons for placing the flow charts into two separate scripts is now discussed:

- The downloading flow chart and uploading flow chart do not share any of the same resources, so they do not have to synchronise with each other at all. By resources it is meant that they do not share any lists of files or directories.
- Resources are not limited on the ground station so running the scripts as separate processes is not a problem.

- By running the scripts as separate processes it is trivial to determine when the script exits for some reason. The script can then be monitored and restarted if it exits for some reason.

- If one script exits, the other script is not affected, which leads to a more robust system.

The sun_monitor_mailbox_upload.py script also checks to make sure that the contents of the ground station's `Outbox` has exactly the same files as those listed in the `Upload List`. If there is an extra file in either the ground station `Outbox` or the `Upload List`, the file will be deleted from the `Outbox` or `Upload List` respectively. This is implemented to help prevent users on the ground station from trying to place files in the system without using the provided scripts sun_sendmail.py and sun_smtpserver.py.

The most complex problem that occurred while implementing the ground station software was discovered while reviewing the code of the system. A race condition was detected when the scripts sun_smtpserver.py, sun_sendmail.py and sun_monitor_mailbox_upload.py accessed the ground station's `Outbox` and Upload List. A race condition is an irregular behaviour of a program caused when the outcome of an action depends upon which of two or more competing processes is granted a resource first.

The race condition is caused because, when a user places a new file into the system, the file is first copied into the `Outbox` of the ground station and then added to the `Upload List`. This happens while the sun_monitor_mailbox_upload.py is busy monitoring the `Outbox` and the `Upload List` for any inconsistencies. Thus, if an undesirable execution sequence is observed the new file that was place into the system by the user could be deleted by the sun_monitor_mailbox_upload.py script before the file has been added to the `Upload List` by sun_sendmail.py or sun_smtpserver.py.

This causes the file to be lost in the system and not sent to the satellite. The problem was solved by using a lock file to control access to a directory or a file. The lock file is just a file whose path name is exactly the same as the file or directory in question with a ".lock" appended to the path name. When a script is going to access the `Upload List` for example, it first tries to obtain a lock on the file before accessing the file. The script can only obtain a lock on the `Upload List` if a lock file for the list does not exist.

A problem that can occur when using a lock file is that, if a process obtains a lock for a file and then exits unexpectedly, a bogus lock file can be left behind. This will then make it impossible for any other process to obtain a lock on the file. This problem was solved by recording the process identity of the process who obtained the lock in the lock file. The process identity of a process is a unique number that is assigned to a process when it is started up by the Linux Operating system.

When a new process tries to obtain a lock on a file and a lock file exists for the file in question, it first checks that the process whose identity is recorded in the lock file is still executing. If the process whose identity is recorded in the lock file is not still executing, the new process obtains the lock for itself. Otherwise the new process will wait until the lock on the file is released.

This chapter described how the system was implemented on the ground station and on the satellite. The testing of the system is described in the next chapter and then it will be shown how a reliable system was created through the testing process.

Chapter 6

Test Environment and System Reliability

The Communications payload is a commercial payload that is running on specialised hardware. It is imperative that all measures are taken to ensure that the system works correctly under varying conditions. This has meant that testing of all the software components has been a very important part of the design process.

This fact has influenced how the complete e-mail system was designed. As outlined in chapter 5, the system was designed with a few independent components. The testing of the system can then be performed in two steps that are now outlined:

- **Structural Testing**
  In this step it is shown that each component of the system performs in the manner that it was designed to perform under all different conditions. The conditions have to be created by the tester, thus the proof of the reliability of the system is only as good as the tests that were implemented.

- **Integration Testing**
  In this step it is proved that the different components of the system work together as expected. This step must also test the system under different conditions.

This chapter will first describe the layout of the test environment that was created and then describes how the testing of the different components of the e-mail system was implemented.

6.1 Test Environment

Figure 6.1 shows the layout of the environment that was used to develop the e-mail system. The layout enables the user to access the OBC using three different paths which will now be discussed.

6.1.1 Ethernet

For the initial development and testing of software it is possible to access the OBC over Ethernet using the Ground Station Equipment Ethernet Interface (GSE-EI). The GSE-EI is a development device supplied by SunSpace. The GSE-EI acts as a router between the CAN bus and the Ethernet.

On this path it is possible to use TCP/IP as the transport and network layer protocols. The developer can thus use any higher level protocol to access the OBC. Files can be transferred using FTP for example and the OBC can be accessed using a remote shell such as `rsh`. The network connection to the OBC through the GSE-EI is substantially faster than the other routes over the audio and RF links.

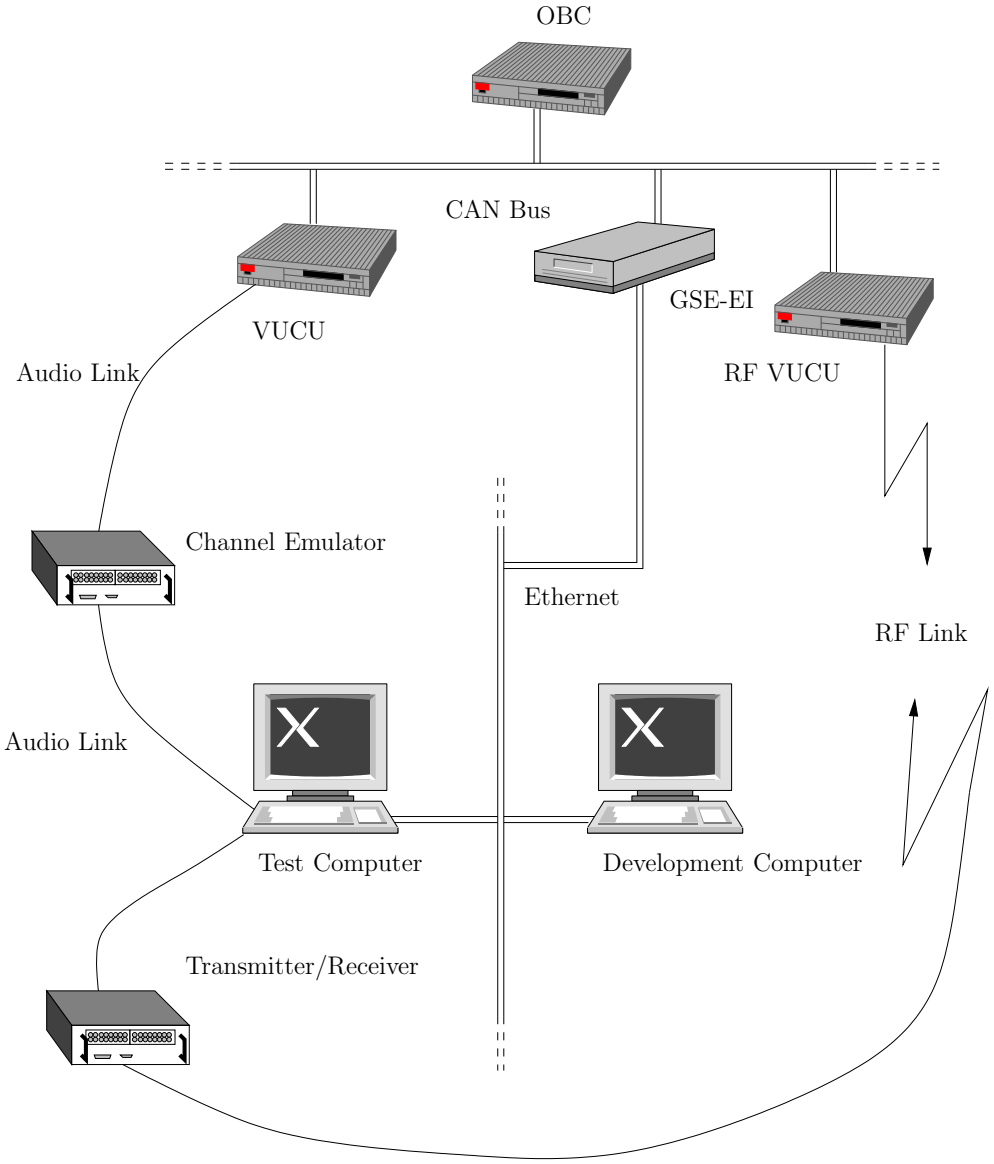

Figure 6.1: *Test setup block diagram.*

6.1.2 Audio Frequency

The route over the audio link was designed to emulate the true RF link between the satellite and a ground station. The sound-card of the test computer was connected to a simple relay circuit which was then connected to the VUCU's audio transmit and receive pins. This was used to emulate a half-duplex link.

The relay circuit was designed to ensure that it is only possible to either have the VUCU transmitting and ground station receiving data at one time or vice versa. Thus a half-duplex link was simulated. A noise generator was also connected to this relay circuit. The signal to noise ratio could be adjusted to create different bit error rates on the channel.

The emulator's default behaviour is to have the VUCU's transmission to sound-card reception path enabled. This causes the audio link to not be a completely accurate emulation of the real satellite to ground station communication link. The reasons for this is now outlined:

- The VUCU transmits HDLC start stop frames continuously when not transmitting data on the audio link. This enables the phase-lock loop in the `soundmodem` software to be continuously synchronised with the VUCU's clock which may improve the performance of the `soundmodem` software.

- It also removes any transient DC offsets and transmission delays that may be introduced by the VUCU's transmitter power amplifier or the ground-station receiver.

Being able to access the OBC through the Ethernet and audio link paths created an environment whereby a systematic development process could easily be followed. Initial testing of software could be tested over the faster CAN bus to Ethernet path and then tested over the audio link.

The RF link could be used after this stage in the development process to make sure that the system worked on the real world system. The RF VUCU was only received late in the development period of the project, thus the audio link was used before the RF VUCU was received.

6.1.3 Radio Frequency

The layout of the test setup that was used for the RF tests is shown in figure 6.1. The layout for the RF link was exactly the same as for the audio link except that the audio link was replaced with the RF link and the audio VUCU was replaced with a RF VUCU.

The tests were performed using a Marconi 2019 signal generator as the transmitter and the Hamtronics R305 UHF FM receiver on the ground station.

6.2 Structural Testing

6.2.1 C Programs

C is a high-level programming language. However C permits many low-level operations, such as pointer manipulations. The use of pointers in the language is often a core reason for problems being introduced into software. Memory leaks can be introduced and access of incorrect memory addresses can also be a problem.

All of the software that was used or written for this project was tested for these sort of problems using the software tool Valgrind. Valgrind is a tool used to debug and profile programs. The functionality of Valgrind that was used was the memory leak detection tool and the illegal access of memory tool.

An example to illustrate how the Valgrind tool can be used to solve common problems in C is now shown:

```
0   >> valgrind --leak-check=full \
1     --trace-children=yes \
2     --show-reachable=yes \
3     --error-limit=no \
4     ./hashsum sha1 LICENSE
5   ...
6   ...
7   ==15605== Invalid write of size 1
8   ==15605==    at 0x804876F: main (hashsum.c:24)
9   ==15605==  Address 0x4162228 is 0 bytes after \
10                a block of size 512 alloc'd
11  ==15605==    at 0x401C422: malloc (vg_replace_malloc.c:149)
12  ==15605==    by 0x804876E: main (hashsum.c:23)
13  508b945e292ebcd6336b50138bfaeac376a24db2  LICENSE
14  ==15605==
15  ==15605== ERROR SUMMARY: 1 errors from 1 \
16                contexts (suppressed: 11 from 1)
17  ==15605== malloc/free: in use at exit: 512 bytes in 1 blocks.
18  ==15605== malloc/free: 2 allocs, 1 frees, 864 bytes allocated.
19  ==15605== For counts of detected errors, rerun with: -v
20  ==15605== searching for pointers to 1 not-freed blocks.
21  ==15605== checked 84,772 bytes.
22  ==15605==
23  ==15605==
24  ==15605== 512 bytes in 1 blocks are definitely lost in loss record 1 of 1
25  ==15605==    at 0x401C422: malloc (vg_replace_malloc.c:149)
```

```
26  ==15605==    by 0x804876E: main (hashsum.c:23)
27  ==15605==
28  ==15605== LEAK SUMMARY:
29  ==15605==    definitely lost: 512 bytes in 1 blocks.
30  ==15605==      possibly lost: 0 bytes in 0 blocks.
31  ==15605==    still reachable: 0 bytes in 0 blocks.
32  ==15605==         suppressed: 0 bytes in 0 blocks.
```

In line 7, Valgrind shows that there was an invalid write to a memory address. It shows the line in the file `hashsum.c` where the error occurred. The error was introduced into the code to illustrate how Valgrind can be used to find mistakes in a program. In line 24, Valgrind shows that 512 bytes were definitely lost. This is caused by a memory leak in the program. This error was introduced because the buffer that had memory allocated to it was not disposed of properly.

The programs that must run on the satellite have to be cross-compiled from Linux to QNX. This can possibly, but very unlikely, introduce problems into the program. Problems can be introduced if, for example, a POSIX system call behaves differently on Linux than on QNX. This should not happen because both Linux and QNX are POSIX compliant, but differences in complex systems such as an operating system can occur.

Valgrind does not have a port to QNX. Thus the integrity of a program is assumed to be correct if it performs correctly on Linux.

Further testing of the Linux tools that were used were not performed because they are standard applications on the Linux environment.

The development of the Ground Station Selection software was handed over to Retief Gerber for completion and the structural testing of his software was handled independently. The control software was tested with the rest of the system in the integration testing and the software was also profiled using Valgrind.

6.2.2 Python Scripts

Unit-testing is a process whereby you test every function and method in a module independently. It is used to validate that every "unit" of a program works correctly to specifications. Unit-testing has many benefits:

- It creates a more disciplined procedure to the development process, because the developer is forced to think about what can go wrong in the software and thus design better code.
- When a change is made to a part of the software, the effect on other parts of the software can quickly be recognised. This promotes an environment where changes to the software are more likely to be implemented because the effect on the rest of the system can be observed.

- The unit-tests also provide a subsequent developer of the software examples of how the different components of the software should be used.

The python scripts that where used to implement the e-mail system on the ground stations where all tested using the standard PyUnit unit-testing framework. Every function was tested using PyUnit.

A code coverage tool is another useful tool that can be used to see how thorough the testing of the software was. It tells the developer which parts of the program where actually executed. By using the code coverage tool and unit-testing, the developer can see how effective the tests were at testing every line of code.

The goal of unit-tests is to test the different parts of the system independently and not to test the interaction between the different parts of the system. The testing of the entire system is described in the integration testing part of this chapter.

An example of the unit-tests for one of the functions in the utils.py file is now shown in the following code extract from the test_utils.py file. The function that is being tested is a utility function that was implemented to abstract how a user application executes an external command from within the python interpreted environment.

test_utils.py implements a PyUnit unit-test by sub-classing the unittest class implemented in the PyUnit package. The `self.assert*` are the assertions that must succeed and are used to ensure that the function behaves correctly.

```
1   ##
2   # Test executing a simple command
3   # and seeing if is successful.
4       def testExecCmd(self):
5           self.initialise();
6           (output,returncode) = utils.execCmd("ls -a");
7           output.remove('.');
8           output.remove('..');
9           pyoutput = os.listdir(".");
10          output.sort();
11          pyoutput.sort();
12          self.assertEqual(output,pyoutput);
13          self.assertEqual(returncode,0);
14
15  ##
16  # Test executing a non existing command and see
17  # that the returncode does not equal 0.
18      def testExecCmdIncorrect(self):
19          ...
20  ##
21  #Test execute command that uses a more complex command, it uses pipe
```

```
22      def testExecCmdPipe(self):
23          ...
24  ##
25  #Test execute command that uses a redirection
26      def testExecCmdRedirection(self):
27          ...
28
```

There are four tests implemented here, the code coverage tool output is shown next for the set of tests that are executed.

```
1   > def execCmd(cmd,nonblocking = 0):
2   >     import subprocess;
3   >     try:
4   >         process = subprocess.Popen(cmd, shell=True,
5   >                                    bufsize=131072,
6   >                                    stdout=subprocess.PIPE,
7   >                                    stderr=subprocess.PIPE);
8   >         pipe = process.stdout;
9   >         pipeErr = process.stderr;
10  >         if not nonblocking:
11  >             process.wait();
12  !     except OSError,msg:
13  !         logging.exception("Failed when calling"+\
14  !                           "subprocess: "+str(msg));
15  !         raise email_exception.EmailException,
16  !                   "The command "+cmd+" failed: "+str(msg);
17  >     if not nonblocking:
18  >         output = [];
19  >         for line in pipe:
20  >             output.append(line.strip("\n"));
21  >         for line in pipeErr:
22  >             output.append(line.strip("\n"));
23  >         return [output,process.returncode];
24  !     else:
25  !         return [process,0];
```

The > means that the line was executed and the ! means that the line was not executed. The only lines that where not executed was lines 12 to 16 and the last two lines. Lines 12 to 16 are only executed if something internal in the subprocess python package fails. The last two lines are only executed if the non-blocking functionality of this function was used and this was never used in the project. They are very simple lines so it assumed that it will work.

This example illustrates how unit-tests do not guarantee that the code will now work in all possible situations. All the important lines of code of the function are executed, but the thoroughness of the tests will only ensure that the specifications of the function are achieved successfully.

6.2.3 KSH Scripts

The functional testing of the KSH scripts is not as structured as the tests that were performed on the ground station python scripts. There are a few reasons for this:

- There are no formal unit-testing frameworks for the Korn Shell.
- The main script GSCommand contains the majority of the complexity of the e-mail system implementation on the satellite. The script does not use many functions and is written in a sequential manner. Thus it is difficult to create tests that test the different parts of the code independently.
- The script is short and simple so errors in the code can easily be isolated in the script. Thus debugging of the script was straightforward.

The main testing of the scripts was done by inspection of the code and many problems were found in this way. An example of such a mistake that was discovered by inspecting the code is shown in the next code segment from the GSCommand satellite Korn Shell script:

```
1  for f in  `cat  $UPLOADFILE | cut -f 1`; do
2      newFile="$SATINBOX/$f-`cat $UPLOADFILE | grep $f | cut -f 2`";
3      echo $NICEOUT
4      echo "GETTING FILE: $f"
5      touch $newFile$FILENOTCHECKED;
6      ...
7      #GET THE FILE
8      ...
9      if test "X`cat $newFile $MAGICFILE | hashsum sha1`" =\
10         "X`cat $newFile.hash`"; then
11         #The file was uploaded successfully
12         #hash for the file passed.
13         ...
14         rm -f $newFile$FILENOTCHECKED;
15         ...
```

This code extract shows the part of the GSCommand KSH script where all the files are uploaded from the ground station that is presently being serviced. Lines 1 and 2 interpret the list of all the files that must be uploaded. Each of the files in the list is then uploaded.

Lines 5 and 14 were originally not present in the code. Lines 9 and 10 checks that the file was uploaded correctly from the correct ground station. This is achieved by ensuring that the file's hash matches up with the hash file that was uploaded.

Later on in the code all the files that have been uploaded are then placed in the correct ground station's outbox. This creates a potential problem.

Any program that runs on the satellite can be terminated by the process monitor at any particular point. Thus in this code extract the script might exit anywhere between lines 5 and 14. ATFTP and TFTP both create empty new files when they start to upload a file and then add the new bytes to the file as the new segments of the file are received. There is no way for the user to know when a file has been completely uploaded.

This characteristic of the TFTP protocol creates a problem if the program terminates between lines 5 and 14 in the original code because the file that was busy being uploaded could be in an inconsistent state. It will then be moved to another ground station's outbox and eventually downloaded, which is something that should not happen.

Lines 5 and 14 creates a transaction out of the upload process. This means that either the entire upload process must succeed, i.e. the file must be uploaded and checked for consistency, or the file must be deleted. The file that is uploaded will only be moved to a ground station outbox if the `$newFile$FILENOTCHECKED` file does not exist, ensuring that only a consistent file will be placed in a ground station's outbox.

The example just described gives an idea of what sort of problems where solved by inspection of the KSH code. The rest of the problems where solved by extensive integration tests described in the next section and the process was assisted by the logging system described in chapter 7.

6.3 Integration Testing

A repeatable and thorough integration test was developed for the system. The test contains two components, namely the test that runs on the OBC and the test that runs on the ground station. The goals of the tests for the ground stations are outlined next:

- They must be able to simulate the different arrival rates of e-mails into the system.
- Logging of events must be thorough and easy to interpret. They must also be recorded so that the data can be analysed at a later stage.
- They must be able to simulate running several different ground stations on the same machine to simplify the tests.
- They must simulate every different e-mail scenario, i.e. message relay from a local user to a local user, from a local user to a user on another ground station, etc.
- They must be able to send files that vary in size with a user defined maximum file size.

- They must be able to send a user defined number of files for a test situation.

The file `send_some_files.py` implemented all of these requirements. The user can specify all the parameters (arrival rate, ground station names, maximum file size, etc.) as arguments to the script. The file creates all the relevant configuration files. Debugging output is saved to separate files for all of the ground stations. Events that occur in the system are recorded using the logging system defined in chapter 7.

The simulation of the arrival of new e-mails into the system was modeled using an exponential distribution function. The exponential distribution function is specified using a single parameter λ which can be viewed as the mean inter-arrival time of events into the system. Viewing the amount of arrivals into the system over a given time T when using an exponential distribution function to determine the inter-arrival times will produce a Poisson distribution [10]. Poisson distributions are often used to model the arrival of data packets into teletraffic systems.

A single Poisson distribution function is used to model the arrival of e-mails into the entire system instead of having a separate Poisson distribution function for each of the ground stations. This does not create any problems for the system because the sum of independent Poisson distribution functions generates another Poisson distribution function [10].

For the entire system to work the OBC must also run some test scripts. This is considerably simpler to design than the ground station tests. The test on the satellite simply runs the ground station selection program on the satellite using the SunSpace process monitor. The Flight Software Tools provided by SunSpace allows a telecommand to be sent periodically to the satellite.

The ground station selection software is configured to be started automatically on boot-up of the OBC by the process monitor. A telecommand is sent to the OBC to reboot the SH4 after a user defined interval. This simulates the fact that you can only communicate with the satellite when it passes over South Africa and the link between the satellite and the ground station is good enough.

In this chapter the procedures that where followed to test the system were described and the next chapter will describe the steps that were taken to ensure that the system can easily be maintained by subsequent developers on the project. The next chapter also describes the logging system that is used to track down problems that may occur during the life span of the project more easily.

The next chapter is included before the results in chapter 8 because the system designed in the next chapter was used to obtain the results given in chapter 8.

Chapter 7

Maintenance

A very important part of any commercial project is to provide a system that is easily maintainable over the entire life span of the project. A thorough logging environment was implemented to create a system that is easily maintained. The logging system is also important to analyse the performance and reliability of the system. Chapter 8 shows these results.

The documentation of code is also very important to create a system that is easily maintained. This chapter will describe how the logging for the system was implemented and briefly describe how the documentation for the code was implemented.

7.1 System Logging

7.1.1 Ground Station

There are two levels of logging found within the system on the ground station.

The first level, called the debug level, is helpful information that is recorded constantly by the various scripts on the ground station. This is information that the developer used to develop the software. This information is recorded to a file that is also rotated as on the satellite. If a problem occurs in the system, these files could be useful to debug the system. They are not of any other use for the user of the system.

The second level is the logging level. The logging level records whenever an important event occurs in the system. The events that occur in the system are described next. The names used for the different events are the actual names that are used to describe the events in the e-mail system software.

- **FETCHED FROM SYSTEM**
  A file is fetched from the system using the script `fetchmail.py`.
- **FAILED PLACE IN SYSTEM(local destination)**
  A file is placed in the system with the destination e-mail address being a local user and the operation fails.

- **PLACE IN SYSTEM(local destination)**
  A file is placed in the system with the destination e-mail address being a local user.
- **FAILED PLACE IN SYSTEM(local destination non-existing)**
  A file is placed in the system with the destination e-mail address being to the local domain and the user does not exist on the local machine and the operation fails.
- **PLACE IN SYSTEM(local destination non-existing)**
  A file is placed in the system with the destination e-mail address being to the local domain and the user does not exist on the local machine.
- **FAILED PLACE IN SYSTEM(external destination)**
  A file is placed in the system with the destination e-mail address being to any e-mail address not on the current machine and the operation fails.
- **PLACE IN SYSTEM(external destination)**
  A file is placed in the system with the destination e-mail address being to any e-mail address not on the current machine.
- **FAILED RECEIVED FILE: (could not move it)**
  A file was received from the satellite and could not be moved to the correct local user's inbox.
- **RECEIVED FILE: (local destination)**
  A file was received from the satellite for a user that exists on the local machine. If the ground station is a not a gateway ground station this event also occurs when the file is received for a non-existing user with the ground stations domain as the domain in the destination e-mail address.
- **FAILED RECEIVED FILE: (forwarding)**
  A file was received from the satellite by a gateway ground station and it failed to be forwarded to the external Internet.
- **RECEIVED FILE: (forwarded)**
  A file was received from the satellite by a gateway ground station and it was forwarded to the external Internet.
- **FILE UPLOADED:**
  The file was uploaded by the satellite.
- **EXTRA FILE IN UPLOADLIST**
  A bogus file was found in the Upload List and was removed from the list.
- **EXTRA FILE IN OUTBOX**
  A bogus file was found in the outbox of the satellite and was deleted from the file system.

The following information about each of the events is recorded: the time of the event, the ground station where the event occurred, the source file name, the source file size, the source file hash sum, the destination file name, the destination file size, the destination file hash sum, the source e-mail address, the destination e-mail address. Only the relevant fields for each event are recorded.

All the events are recorded within a Python script, thus an extremely easy way to record the event to a file is to record the event as a Python pickle. A Python pickle is a serialised form of a Python object that can be written to a file and then read from a file into a Python object at a later stage. These pickles of the event are recorded to the file system by default when they occur.

The object that stores the event also provides a method to log the event to a Structured Query Language (SQL) database. The events can then be loaded into a database for ease of interpretation using SQL. The system can be configured to log each event to a pickle file, a database or both when they occur. If the event is logged to a file then it can later be loaded into a database at any time.

The Python script `print_logfile.py` is provided to interpret the pickle files. The pickled objects can be printed as strings, which can also be loaded into a spreadsheet application like OpenOffice or Microsoft Excel. The Pickles can also be loaded directly into a mySQL database. mySQL is a SQL Database Management System (DBMS) licensed under the GNU General Public License (GPL).

This logging system is essential for the stress testing of the e-mail system. It is possible for example through the use of SQL statements to determine which files are uploaded to the satellite and not downloaded from the satellite. The list of possible interpretations of the events goes on and are easy to design using SQL. This logging system was used extensively to produce the results that are seen in the next chapter. A few examples of the SQL statements that are used to obtain the results is given in chapter 8.

By default the events are recorded to the local machine. Thus not all events will be observable in the final system unless the events from all ground stations are manually retrieved and then uploaded into a central database. For the testing environment where the tests run on the same computer this is not a problem.

7.2 System Documentation

The e-mail system is also documented in the actual code so that a subsequent developer will find it easier to maintain the system. The Doxygen documentation system is used to document the Python code. Doxygen is a document generator that extracts documents from comments found within the source code of a project. Doxygen was used because it provides a HTML format of the documentation that is easy to navigate and understand.

The Korn Shell scripts are documented in the actual code where applicable and no document generator is applied to the Korn Shell scripts.

This chapter provided a description of the logging system which is essential to the analysis of the system that is provided in the next chapter.

Chapter 8

Test Results on the Integrated System

The SH4 processor has the functionality to enable or disable the cache on the processor. The cache of the SH4 is susceptible to single event upsets (SEU). Single event upsets are caused by radiation when the satellite is in space. The SH4 processor performs in the order of five times slower when operated with the cache off compared to when the cache is on (see table 8.3).

Most of the tests in this chapter are run when the cache on the SH4 is disabled. This is used to determine how the system will work in the worst case scenario.

The first part of the chapter will give some results when the complete e-mail system was integration tested over the Ethernet, audio and RF link.

The second part of this chapter performs some comparison tests between NFS and ATFTP to show why TFTP was chosen as the primary protocol to transfer files between the satellite and the ground station.

The final part of the chapter will provide an analysis of the execution time of the satellite software. This information is given to help determine where most of the execution time is spent and will help determine where the system can be optimised.

8.1 Integration Test Results

The complete system was first tested over the Ethernet and audio communication paths in figure 6.1 and then on the RF link with the RF VUCU. Rows one to four in table 8.1 shows the results of running the script `send_some_files.py` using the Ethernet link. The inter-arrival time and number of ground stations were changed to see how this affects the performance of the system. The files are all transferred successfully. To determine if the files

Table 8.1: *Test results for integration tests over the different links. Each ground station has three different users. The* `send_some_files.py` *script was used to generate the results. The satellite hardware was rebooted every 6 minutes to simulate the communication window caused by the satellite's orbit. The files have a maximum size of 4 kB. All files were transmitted successfully for all the tests.*

Link	Ground Stations	Mean Inter-Arrival Time (sec)	Files Transferred successfully	Average Transfer Time [h:m:s]	Maximum Transfer Time [h:m:s]	Minimum Transfer Time [h:m:s]	Satellite Reboots (Approximate)	Test Duration [h:m:s]
Ethernet	3	60	666	00:10:16	00:38:32	00:00:21.69	168	17:02:12
Ethernet	6	60	666	00:19:49	01:03:49	00:01:00.08	167	16:50:55
Ethernet	3	30	666	00:18:55	00:53:05	00:01:22.65	92	08:40:09
Ethernet (cache on)	3	60	673	00:00:41	00:02:06	00:00:12.19	165	16:43:52
Audio	3	60	73	00:13:08	00:31:50	00:01:34.70	16	01:32:17
Audio (cache on)	3	60	71	00:03:45	00:11:20	00:01:10.71	16	01:47:30
RF	3	60	65	00:12:46	00:28:15	00:02:23.24	16	01:44:33

are transferred successfully the following SQL statement is used:

```
1  select ev.srcFile from event_log ev
2      where ev.event=11 AND
3            ev.dstAddress NOT LIKE '%@gw.sumbandilasat.co.za' and
4       ev.srcFile not in
5    (select dv.srcFile from event_log dv
6          where dv.event >=8  and
7          dv.event <= 10)
```

The event 11 in line two of the SQL statement is an upload event and events between 8 and 10 are download events. Line 3 ensures that the e-mail is not sent to the gateway user. E-mails to the gateway user are not forwarded down to the ground stations. E-mails to the gateway user on the satellite are used to update the satellite software. The SQL statement ensures that all files that are uploaded to the satellite are downloaded from the satellite later.

Validity of this SQL statement can be tested by removing a download event from the database. The file whose download event was deleted will then be displayed as the output of the SQL statement.

The files are also tested to make sure that they are not corrupted during transmission by comparing the hash sum of the original file with the delivered file using a SQL statement again. All the other columns in table 8.1 are generated using SQL statements except for the "Satellite Reboot" column which is determined from the SunSpace Flight Software Tools.

The first row of table 8.1 is used as the basis against which to compare the results obtained in rows two, three and four.

The satellite reboots 168 times during the test in row one. The satellite orbits over South Africa four times a day and has to share these orbits with the other payloads on the satellite. If the communication payload is able to use two of the orbits on average every day, then this test simulates 84 days of the satellite's life span.

The six minute window that is used for the satellite communications window in this test is very conservative. This six minute window includes the boot-up of the satellite OBC and the execution of the `InitCommand` Korn Shell Script. These scripts will all be run before the satellite enters the communications window in the real system so the throughput should be higher.

The average transfer time of a file almost doubles when the number of ground stations double, as can be seen in row two in table 8.1. This is expected because the ground station selection software has to process more ground stations between successive services of a specific ground station. The system still performs without error.

When the mean inter-arrival time of new files being placed in the system is decreased to 30 seconds, the average transfer time of a file increases. The effect of halving the inter-arrival time appears to have approximately the same affect as doubling the number of ground stations that are going to be serviced. These results can be used to help configure the final e-mail system when it is deployed. The administrator of the system will be able to restrict the number of files that are placed in the system to accommodate more ground stations being added to the system.

Row four in 8.1 shows how the e-mail system performed over the Ethernet link when the cache was enabled. The efficiency of the system was dramatically improved when the cache was enabled.

Row five in table 8.1 shows that the e-mail system communicated correctly over the audio link, which simulates a half-duplex link. All files where transmitted successfully. Fewer files were used in the audio link tests when compared to the Ethernet tests. The tests over the audio link were performed to give confidence in the fact that the tests over the Ethernet and audio link are equivalent.

Row six in table 8.1 shows that the e-mail system communicated correctly over the RF link. The file transfer times for the audio and RF link tests where similar in duration which is understandable because the audio link was designed to emulate the RF link.

8.2 ATFTP vs NFS

Figure 8.1 and figure 8.2 show the communication times when NFS and ATFTP attempt to transfer files of different sizes over the audio link. All the tests in this section are performed when the cache was turned off on the SH4. Different bit error rates are introduced into the channel by changing the amount of noise introduced into the channel by the channel

emulator in figure 6.1. The bit error rates are determined empirically by measuring the packet throughput from end-point to end-point of the system. The packet success rate (P_s) can then be determined.

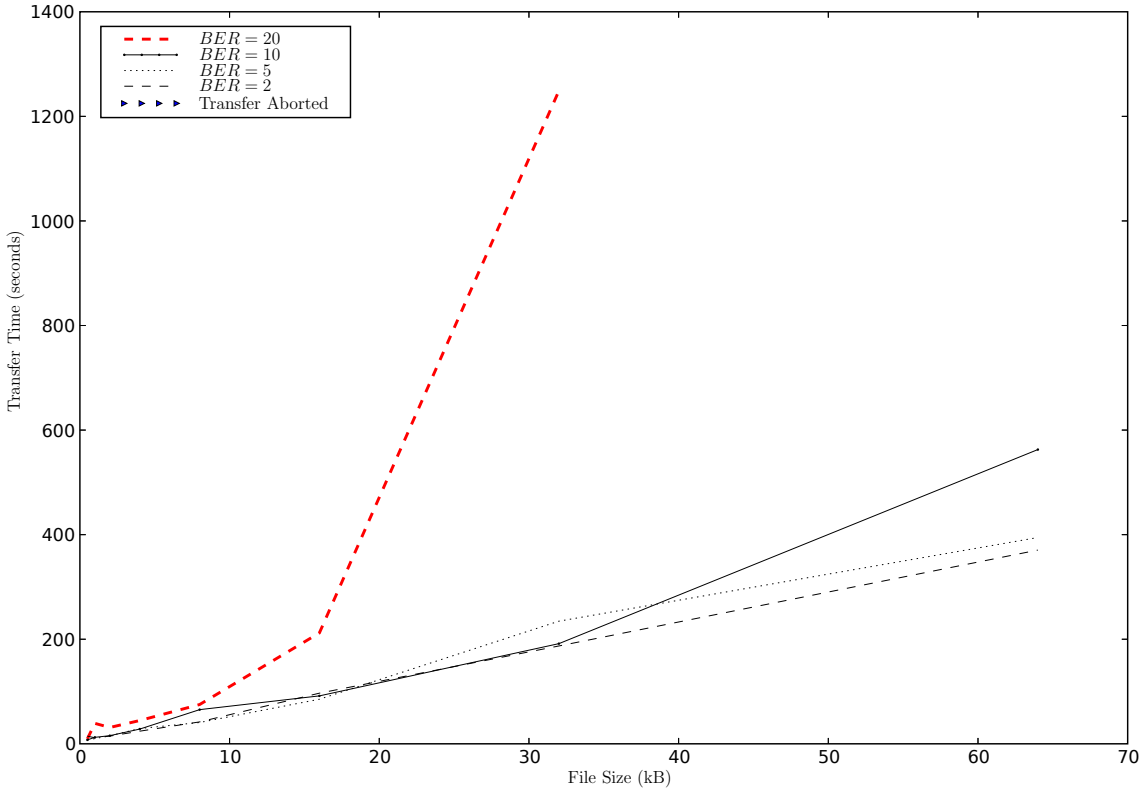

Figure 8.1: *NFS communication times for different bit error rates ($BER \times 10^{-5}$). NFS tries to transfer the file until it is transferred completely. NFS will never cancel the file transmission in the configuration used for this test. Thus the communication time increases as the bit error rate increases. 0.5, 1, 2, 4, ... and 64 kB sized files were used to obtain the results. One file was transferred for each file size.*

P_s can be used to determine a rough estimate of the BER by using the following formula where P_n is the probability of receiving no errors and N is the number of bits in the packet.

$$\begin{aligned} P_s &= P_n \\ &= \binom{N}{0}(BER)^0(1-BER)^N \\ &= (1-BER)^N \\ BER &= 1-\sqrt[N]{P_s} \end{aligned} \tag{8.1}$$

The Bernoulli trial formula [17] is used in step two in the formula. The packet size that was

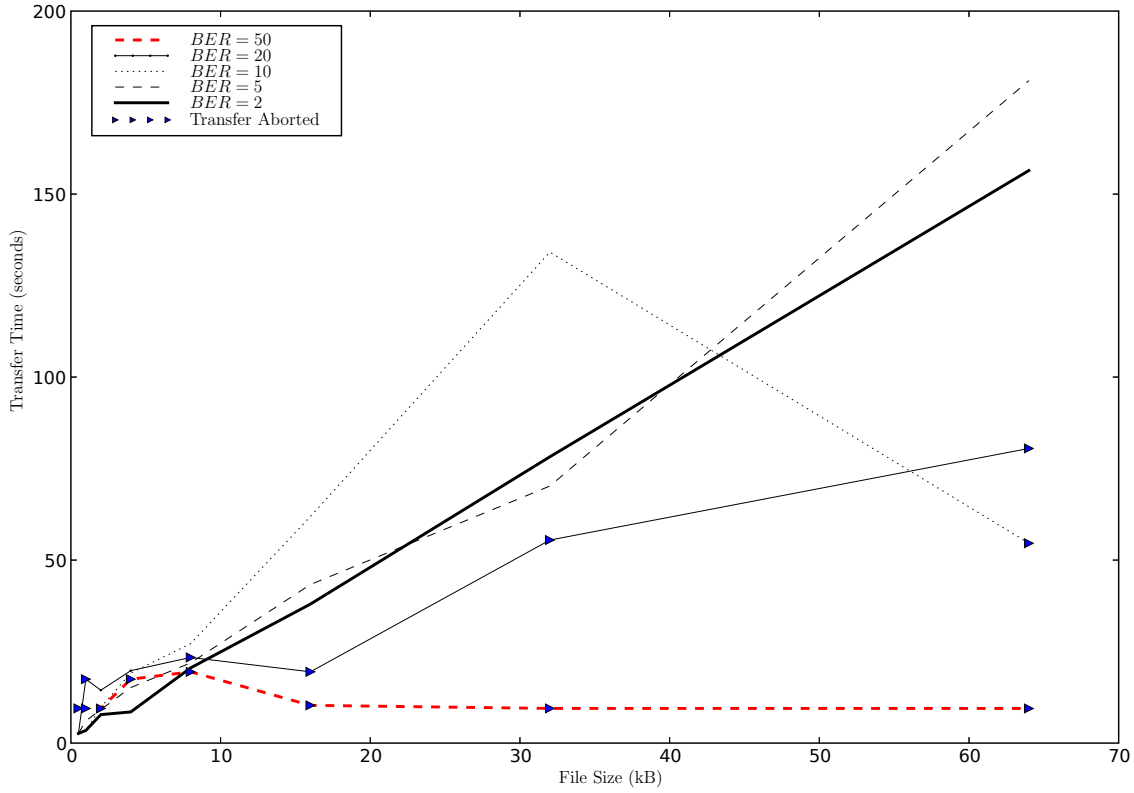

Figure 8.2: *ATFTP communication times for different bit error rates (BER$\times 10^{-5}$). ATFTP has a timeout mechanism which causes the transfer of files at high bit error rates to be aborted. This figure just shows the actual time that was spent accessing the channel. 0.5, 1, 2, 4, ... and 64 kB sized files were used to obtain the results. One file was transferred for each file size.*

used in the test was 157 bytes long. This caused the value of N used to determine the bit error rate in figures 8.2 and 8.1 to be 157×8 and a 100 packets where sent to determine P_s.

In figure 8.1 it can be seen that the transfer time of files using NFS increases as the bit error rates increases. When the bit error rate is equal to 20×10^{-5} the transfer time increases dramatically.

When observing the network traffic that is generated by the NFS protocol over the audio link at low bit error rate a lot of retransmissions are also observed. These retransmissions should be minimal because the link is almost perfect but the observed audio link shows that the retransmissions occurred often. This causes the transfer times of files using NFS to vary which can be seen in Table 8.2. The transfer time of the 0.5 kB file is slower than the 1 kB file and almost equal to the 2 kB file. This variance in the transfer times is caused by the retransmission of packets over the link.

Table 8.2: *Transfer times (seconds) for files of different sizes (kB) at a BER equal to* 1×10^{-5} *using NFS and ATFTP. The Mount column and Unmount column gives the amount of time it takes to mount and unmount the remote file system.*

Protocol	Mount	0.5 kB	1 kB	2 kB	4 kB	8 kB	16 kB	32 kB	64 kB	Unmount
NFS	3.82	14.66	11.53	14.72	24.16	41.91	96.85	187.12	370.51	0.54
ATFTP	0	2.62	3.46	7.78	8.51	20.55	37.97	78.22	156.43	0

Only one attempt to transfer a single file was used to obtain the information shown in figures 8.1 and 8.2 because the accuracy of the transmission times is not an important parameter to determine. The figures only attempt to show the trend that ATFTP and NFS show as protocols.

Figure 8.2 shows the transfer times of files using ATFTP over the channel at different bit error rates. The first thing to notice is that the transfer times are significantly faster than NFS which can also be seen in Table 8.2. ATFTP also has no mounting and unmounting of the file system to add to its communication time.

The transfer times of files in figure 8.2 increase as the BER increases. When the BER is 10×10^{-5}, ATFTP times out when the 64 kB file is transferred. The transfer of the file is aborted. When the BER is greater than 20×10^{-5}, ATFTP times out for all the files in this test.

The time spent trying to transfer the files reaches an almost constant value when the BER is 50×10^{-5}. This is good because if the link to a ground station is bad the satellite will not waste too much time trying to service the ground station. The link to a specific ground station can improve and decrease as the satellite communications window moves over the ground station. Thus this does not mean that the ground station will not be serviced, because on the next pass of the satellite the ground station could get serviced with a better link quality.

The problem with ATFTP is that it times out if it does not receive a reply from the server within a user-defined number of attempts. This causes ATFTP to not be very robust when burst errors are observed on the link. NFS is more robust to burst errors but the significant increase in transmission times for NFS offsets this benefit.

The satellite has a restricted communications window when passing over South Africa. This is estimated to be between 6 and 12 minutes depending on the observed signal to noise ratio on the satellite link [26]. The final communications window time will have to be empirically determined when the satellite is actually in orbit. The transmission time for a file should be an order of magnitude smaller than this communication window time to enable many ground stations to be serviced in a single orbit. Thus from figure 8.2 an optimum maximum file size can be chosen to enable the e-mail system network to be efficient.

From these results it can clearly be seen why ATFTP was chosen as the transfer method.

It is significantly faster than NFS. An analysis of the satellite scripts is given in the next section of this chapter.

8.3 Transmission and Execution Times

A few tests to determine where execution time is spent on the satellite software are given in this section.

Table 8.3: *Comparison between running times of satellite scripts when started manually and when started by the ground station selection software. There were no files to be transferred. The average of ten executions of the scripts was used to determine the execution time. A port of the* `GSCommand` *to the C language is also provided for comparison.*

Command	Execution Time (seconds) Cache off	Execution Time (seconds) Cache on
`InitCommand`	24.846	5.563
`PreComCommand`	5.903	1.335
`GSCommand`	17.277	5.374
`PostComCommand`	3.278	0.784
Total Manual Time (Korn Scripts)	51.304	13.056
`GSCommand_c` (In C)	17.844	5.353
Ground Station Selection	55.682	13.975

The tests in this section try to determine where most of the execution time is spent when the scripts are executed on the satellite. Table 8.3 shows the execution times of the various scripts on the satellite.

The total time spent executing from start-up to termination when starting the scripts manually on the command line is approximately 51.304 seconds when the cache is disabled. The execution time when the ground station selection software is executed on the satellite and one ground station is serviced is approximately 55.682 seconds when the cache is disabled. This includes calculations to choose the ground station, the interaction with the process monitor and updating of the administration files. The extra time spent processing when using the ground station selection seems to be acceptable and does not appear to be a bottle-neck in the system.

The `GSCommand` script was ported to C to determine if this would create more efficient software on the satellite when compared to the Korn Shell scripts. From table 8.3 it can be seen that the C port of the `GSCommand` has approximately the same execution time as the Korn Shell `GSCommand`. Thus the Korn Shell does not cause a significant bottleneck in the system.

The biggest benefit to the performance of the system can be achieved by running the SH4 with the cache enabled.

Table 8.4: *Comparison between running times of the* `GSCommand` *when there are different numbers of files to transfer. The test is run over the audio link with copies of the same file of size 2kB being transferred.*

Cache	File Upload	File Download	Execution Time (seconds)	Transmission Time (seconds)	Percentage Transmission
off	1	0	39.45	13.4	33.98
off	0	1	34.72	17.1	49.25
off	1	1	58.13	27.57	47.43
off	3	3	120.97	69.06	57.09
on	3	3	61.51	49.67	80.75

Table 8.4 shows the execution time of the `GSCommand` when there are different numbers of files to transfer. The `GSCommand` is the only script on the satellite whose execution time will be influenced if there are files to be uploaded or downloaded. The `InitCommand`'s execution will be influenced if the `GSCommand` is terminated at a specific point in its execution. The `InitCommand`'s execution time is irrelevant because it can be executed before the satellite enters the communication window.

From the table it is seen that the downloading of files is quicker than the uploading of files. This can be deduced by looking at the amount of steps that are performed in the satellite download flow chart in figure 4.1 and the satellite upload flow chart in figure 4.4. There are much fewer steps in figure 4.1 than in figure 4.4 which translate to less complex Korn Scripts used to implement the flow chart.

If there are few files to upload or download then the link is utilised very inefficiently. The utilisation percentage of the link increases as the amount of files in the upload and download queues increases. This is a good trend because it shows that the system will perform more efficiently when the files to upload and download increases.

When the cache is enabled on the SH4 the efficiency of the system increases dramatically. The average execution time decreases and the percentage of the execution time spent in transmission increases.

This chapter has shown that the system performs correctly. The system was stress-tested over the Ethernet, audio and RF link. The system performed correctly on all three of the different links. An execution profile of the satellite software was also performed to aid further development of the system. The conclusion in the next chapter will provide a summary of the design and implementation of the satellite e-mail system.

Chapter 9

Conclusion

This thesis has provided a description of the design and implementation of a rural e-mail system for the use on the Sumbandila Satellite.

9.1 Summary of the conducted work

The thesis was broken up into three sections. In the first section of the project the hardware and software that was used on the satellite was described. The design of the equivalent system implemented on the ground station was then provided.

The first part of the thesis included the use of an open source software modem called `soundmodem`. `soundmodem` was modified for use with the SunSpace VUCU and data-link layer protocols. It was shown that the OSI layer that was provided by the software and hardware on the satellite restricted the use of protocols that were able to be used in the e-mail system. The e-mail system was restricted to using UDP as the transport layer protocol. TFTP and NFS were chosen as the application layer protocols to achieve communication between the satellite and the ground stations. These protocols both use the communications channel in a half-duplex manner.

The second part of the thesis provided the design and implementation of the e-mail system that was used on the satellite and on the ground station. The satellite software was designed to be as simple as possible to try reduce the complexity of the system on the satellite. The satellite was designed to control the communication with the ground stations. The design choice was made to view all e-mail transfers as file-transfers to create a simpler system and a more robust system.

A completely reliable system was designed where all file-transfers were acknowledged at all stages in the ground station to satellite to ground station relay process. Python scripts were used to implement the critical part of the design on the ground stations. Standard Linux applications were used where possible. The satellite software was implemented using Korn Shell scripts and the C programming language.

The third part of the thesis provided a description of the methods used to test the system and to create a maintainable system and then provided the results for the tests that

were performed on the system. The testing of the e-mail system was performed thoroughly and attempts to simulate what will happen when the e-mail system is operational in the real-world environment. The results proved that the system performed well under different conditions.

9.2 Recommendations

The e-mail system was designed to reach a state where it is reliable and performs correctly. The system is not optimised and there are areas where the system can be improved. A few recommendations where possible improvements to the satellite software can be made will now be provided:

- The time-out used in ATFTP is susceptible to burst errors as can be seen in figure 8.2. ATFTP aborts the file transfer if a user-defined number of timeouts occur in succession. Thus the link could be very good and then degrades in quality for a short period causing ATFTP to abort the transfer. This is not good because the overall link quality is good. ATFTP could be modified to use a more advanced system of link quality analysis to attempt to create a system that is more robust towards burst errors. The link quality analysis could also be used to improve the ground station selection process and help configure the ground stations to use the link more effectively.

- Different compression schemes used to compress files before transmission could be used on the ground station software to decrease the file size that is transmitted to the satellite.

- The effect of using the cache on the SH4 on the satellite must be determined. If the occurrences of single event upsets are acceptable then the Korn Shell scripts on the satellite are close to being optimal. If the cache on the satellite is disabled then optimisation of the Korn Shell scripts can have an impact on the efficiency of the system.

- If a file transfer fails half-way through the transfer of a file when using ATFTP and the transfer is restarted, the entire file has to be retransmitted to the satellite. This is inefficient because the link is unreliable and this could potentially happen regularly. An improvement to ATFTP to remove this problem could be implemented as an update to the system at a later stage.

9.3 Final Remarks

Standard protocols and programs were used right through-out the project design to attempt to improve the reliability of the system. The development time of the system was reduced because software was reused where possible. The design of communication protocols is not

trivial and using TFTP for the communication protocol saved a large amount of development time.

The costs of a ground station was greatly reduced because the ground station OSI layer was largely implemented in software. Open source software was used for the ground station software as far as possible and showed what a powerful force open source software is becoming in the industry. The system was thoroughly tested and proven to work correctly. The goal to design a reliable and working e-mail system was thus achieved.

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